

PHOTOGRAPH THIS SHEET

AD-A223 720

DTIC ACCESSION NUMBER

LEVEL

DTIC FILE COPY

INVENTORY

AFOSR 90 0695 APP.D PT.I
DOCUMENT IDENTIFICATION
1989

DISTRIBUTION STATEMENT A

Approved for public release;
Distribution Unlimited

DISTRIBUTION STATEMENT

ACCESSION FOR

NTIS GRA&I
DTIC TRAC
UNANNOUNCED
JUSTIFICATION

BY

DISTRIBUTION/

AVAILABILITY CODES

DISTRIBUTION

AVAILABILITY AND/OR SPECIAL

A-1

DISTRIBUTION STAMP

DTIC
COPY
INSPECTED
6

DTIC
ELECTE
JUN 27 1990
S E D

DATE ACCESSIONED

DATE RETURNED

REGISTERED OR CERTIFIED NUMBER

DATE RECEIVED IN DTIC

90 06 25 101

PHOTOGRAPH THIS SHEET AND RETURN TO DTIC-FDAC

AD-A223 720

APPENDIX D

PT. I

CERTIFICATIONS AND CONCURRENCE

Approved for public release,
distribution unlimited.

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
NOTICE OF TRANSMITTAL TO TRG
This technical report has been reviewed
and approved for public release under
AFR 180-12.
Chief, Technical Information Division

APPENDIX D *PT. I*

CERTIFICATIONS AND CONCURRENCE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public Reporting Burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Washington Headquarters Service, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE	3. REPORT TYPE AND DATES COVERED Annual	
4. TITLE AND SUBTITLE Laboratory Graduate Fellowship Program <i>PT I</i>			5. FUNDING NUMBERS 61102F 2306/06 3484/06	
6. AUTHOR(S) Dr Darrah, Lt. Col Claude Cavender				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Universal Energy Systems Inc. AFOSR-TR.			8. PERFORMING ORGANIZATION REPORT NUMBER 90 0695	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/XOT Bld 410 Bolling AFB, D.C. 20332-6448			10. SPONSORING/MONITORING AGENCY REPORT NUMBER F49620-86-C-0127	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for Public Release			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 400 words) See Attached				
14. SUBJECT TERMS			15. NUMBER OF PAGES	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT N/A	

I. INTRODUCTION

Critical to the success of the Air Force Office of Scientific Research (AFOSR) mission is the ability of AFOSR to draw upon the research community in the United States to respond to its needs. In recent years, however, the number of U. S. citizens seeking advanced degrees in the areas of Air Force research interests has been decreasing. This refers specifically to the number of U. S. citizens obtaining Ph.D. degrees in areas of mathematics and science that are of interest to the Air Force. This situation points toward the potential problem of a future shortage of qualified researchers in areas critical to the nation's security interest.

To address this problem, the United States Air Force Laboratory Graduate Fellowship Program (USAF/LGFP) was established. The contract is funded under the Air Force Systems Command by the AFOSR. The program annually provides three-year fellowships for at least 25 Ph.D. students in research areas of interest to the Air Force. Universal Energy Systems, Inc. (UES) has completed the third year of the three-year LGF program contract.

This report, prepared in compliance with contractual requirements, covers the third year of the program which now sponsors 27 first-year participants as well as 25 second-year fellows and 22 third year fellows for a total of 74 active fellowships. The report addresses an overview of the administration tasks, statistics on the 1989 awards, profiles of all the fellows, and summarized results of the evaluation process. Materials deemed inappropriate for inclusion in the main body of the report, such as samples of forms, complete questionnaire results, etc., are included in the appendices.

II. ADMINISTRATION

The administration of the LGF program is conducted from the Dayton offices of UES. The staff consists of Mr. Rodney C. Darrah, Program Manager; Ms. Judy Conover, Program Administrator; and support personnel. Most members of the 1989 program administration team have been involved with the project since award of the contract to UES. This element of an experienced, stable staff ensures program continuity and contributes to successful operation of administrative tasks.

The primary tasks in managing the program consist of advertising (which includes compiling and updating a mailing list, and preparing and distributing ads, flyers, and

CONCURRENCE FORM

The School of Aerospace Medicine requests the continuation of the AFOSR fellowship for Mr. David J. Linden, studying Neurophysiology at Northwestern University.

Give a brief statement of laboratory and/or Mr. David Terrion's (fellow's mentor) involvement with Mr. David J. Linden.

Mr. Linden has continued to manifest superior academic and investigative talents. His many published works have brought distinction to the USAF Laboratory Graduate Fellowship Program and confirm his potential to be a leading neuroscientist in the future.

During the 20th Annual Meeting of the American Society of Neurochemistry (6-10 March 1989), Dr. Terrian had the opportunity to carefully review Mr. Lindens' academic progress with his advising professor, Dr. Aryeh Routtenberg. However, because Mr. Lindens' research makes extensive use of electrophysiological techniques that Dr. Terrians' laboratory is not prepared to support, no direct interaction between these two individuals has been arranged.

Billy E. Welch 29 April 89

Chief Scientist

Date

Daniel P. Terrion 4/11/89

Mentor

Date

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. David J. Linden

University: Northwestern University

Subcontract: S-789-000-001

Fellow to complete

1. Courses - Give description of courses and grades received (Attach sheet if extra space is needed)

RESIDENT RESEARCH CONTINUATION,
NO. GRADE

2. Give a detailed description of research and progress toward dissertation. (Attach sheets if extra space is needed)

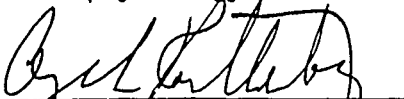
SEE ATTACHED SHEET

"I certify that all information
stated is correct and complete."


Signature/Fellowship Recipient

DAVID LINDEN
TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mr. David J. Linden is making satisfactory academic
progress toward a Ph.D. in the area of Neurophysiology in the discipline
of Neurophysiology for the Winter 1989 quarter."


Signature/Advising Professor

ARYEH ROUTENBERG
TYPED NAME/TITLE OF ADVISING
PROFESSOR

PROFESSOR OF PSYCHOLOGY
& NEUROBIOLOGY / PHYSIOLOGY

LLD/sdp 4649C

My recent research has examined the role of a newly discovered class of protein kinase C activators, the cis-fatty acids, in regulating isolated ionic currents in cultured neurons. This research has been undertaken using the whole-cell patch clamp technique as applied to cultured neuroblastoma cells. My major findings are outlined on the following pages, excerpted from a manuscript recently submitted for publication. My present research involves expanding the investigations detailed below to include currents carried by the calcium ion.

Summary

1. Activation of protein kinase C (PKC) by phorbol esters or diacylglycerols has been shown to modulate a number of ionic currents carried by Ca^{2+} , K^{+} , and Cl^{-} . Recently, it has been demonstrated that PKC may be activated by cis-fatty acids (c-FAs) in the absence of either phospholipid or Ca^{2+} . We wished to determine if this new class of PKC-activating compound would also modulate ionic currents, and if so, to determine the nature of that modulation. To this end, we applied the whole-cell patch clamp recording technique to N1E-115 neuroblastoma cells differentiated in 4% dimethylsulphoxide (DMSO).
2. Analysis of families of currents evoked under voltage clamp by depolarizing steps from a holding potential of -85 mV during application of 5 μM oleate (a c-FA) showed a 36% reduction of the peak inward current with no shift in either the peak or the reversal potential of the current-voltage (I-V) relation and no alteration of outward current.
3. As previous work has shown the inward current of this cell to be largely carried by Na^{+} , we sought to record the isolated Na^{+} current by application of external Mg^{2+} , internal F^{-} and tetraethylammonium (TEA), and the replacement of internal K^{+} with N-methylglucamine. The isolated Na^{+} current recorded in this manner was completely and reversibly abolished by tetrodotoxin or removal of external Na^{+} , and was unaffected by application of external TEA.

4. Application of the c-FAs oleate, linoleate, and linolenate reversibly attenuated voltage-dependent Na^+ current with approximate ED_{50} 's of 2, 3, and 10 μM respectively. Elaidate (a trans-isomer of oleate) and stearate (a saturated fatty acid) which do not activate PKC, had no effect. Since cis-fatty acids are known to fluidize membranes, as well as to activate PKC, we sought to dissociate these functions by applying compounds that fluidize membranes but do not activate PKC: methyloleate and lysophosphatidylcholine. Neither compound affected Na^+ current when applied at concentrations of 1-5 μM .

5. In contrast to c-FAs, three classical PKC activators, phorbol-12,13-dibutyrate, phorbol-12,13,-diacetate, and 1,2-oleoylacetyl glycerol (OAG) were found to have no effect on the voltage-dependent Na^+ current when applied at 10nM-1 μM (phorbol esters) or 1-150 μM (OAG) for incubation periods up to 1 h.

6. The PKC inhibitors polymyxin B and H-7 were seen to block the attenuation of the Na^+ current by c-FA in a dose-dependent manner, with maximal inhibition occurring at doses of 50 and 10 μM , respectively. The cyclic nucleotide-dependent protein kinase inhibitor H-8 was much less effective in blocking the c-FA effect.

7. In another attempt to determine whether the c-FA effect was mediated by PKC, chronic (24 h) exposure to 1 μM phorbol ester was employed to down-regulate this enzyme. This treatment did not alter the baseline characteristics of the isolated Na^+ current, but was

effective in blocking the attenuation of Na^+ current produced by subsequent application of c-FA.

8. Taken together, these data suggest two broad classes of explanation. First, c-FA attenuation of the Na^+ current could be mediated in part through a non-PKC mechanism. The second explanation, which we favor, is that activation of the PKC family of enzymes by c-FAs and the classical PKC activators (phorbol esters, diacylglycerols) could result in different patterns of substrate phosphorylation such that c-FA activation of PKC produces attenuation of the Na^+ current in N1E-115 cells, while stimulation of PKC by classical PKC activators does not.

Short Communications

NMDA receptor blockade prevents the increase in protein kinase C substrate (protein F1) phosphorylation produced by long-term potentiation

David J. Linden, Ka L. Wong, Fwu-Shan Sheu and Aryeh Routtenberg

Cresap Neuroscience Laboratory, Northwestern University, Evanston, IL 60201 (U.S.A.)

(Accepted 26 April 1988)

Key words: *N*-Methyl-D-aspartate; Protein kinase C; Protein F1; Long-term potentiation

Recent evidence has implicated activation of the *N*-methyl-D-aspartate (NMDA) class of glutamate receptor in the initiation of hippocampal long-term potentiation (LTP), an electrophysiological model of information storage in the brain. A separate line of evidence has suggested that activation of protein kinase C (PKC) and the consequent phosphorylation of its substrates is necessary for the maintenance of the LTP response. To determine if PKC activation is a consequence of NMDA receptor activation during LTP, we applied the NMDA receptor antagonist drug, DL-aminophosphonovalerate (APV) both immediately prior to and following high frequency stimulation, resulting in successful and unsuccessful blockade of LTP initiation, respectively. We then measured the phosphorylation of a PKC substrate (protein F1) in hippocampal tissue dissected from these animals. Only successful blockade of LTP initiation by prior application of APV was seen to block the LTP-associated increase in protein F1 phosphorylation measured *in vitro* ($P < 0.001$ by ANOVA). This suggests that NMDA receptor-mediated initiation triggers maintenance processes that are, at least in part, mediated by protein F1 phosphorylation. These data provide the first evidence linking two mechanisms associated with LTP, NMDA receptor activation and PKC substrate phosphorylation.

Hippocampal long-term potentiation (LTP) is a model system of neuronal information storage in which brief high-frequency stimulation delivered to an afferent pathway produces a persistent increase in the efficacy of synaptic transmission². Recently, evidence has emerged for pharmacologically separable processes of initiation and maintenance of this potentiated response. Blockade of the *N*-methyl-D-aspartate (NMDA) receptor by application of the antagonist drug, DL-aminophosphonovalerate (APV), prior to high-frequency stimulation has been shown to reversibly block the initiation of the potentiated synaptic response^{5,10}. However, NMDA receptor activation appears to be important only in the initiation of LTP, as application of APV has no effect on the potentiated response once established.

Conversely, several lines of evidence indicate that activation of protein kinase C (PKC) is critical for the

maintenance, but not the initiation of LTP^{1,14,15,17,18,24}. In contrast to NMDA receptor antagonists, PKC inhibitors given prior to high-frequency stimulation leave the initiation of the potentiated response unaltered, but can eliminate LTP when applied 10 min after high-frequency stimulation¹⁸. Consistent with this observation, PKC activators have been shown to facilitate the maintenance but not the initiation of LTP^{14,15,24}. Finally, LTP causes an increase in PKC activation¹ and the consequent phosphorylation of a PKC substrate, protein F1¹⁷, which is positively correlated with the maintenance of the potentiated response.

Is PKC activation/protein F1 phosphorylation, which appears to be critical for the maintenance of LTP, a consequence of NMDA-receptor mediated initiation processes, or are these two mechanisms initiated in parallel? To address this question we as-

sayed the phosphorylation of protein F1 in hippocampal tissue from intact animals in which LTP was produced, in which LTP was blocked by prior application of APV, and in which APV applied after high frequency stimulation failed to block LTP.

Experiments were performed in the intact dentate gyrus of urethane-anesthetized rats as previously described¹⁵. A multi-barrelled micropipette for recording field potentials and pressure ejection of drugs was placed in the dentate gyrus molecular layer, where perforant path fibers terminate. A twisted-wire bipolar stimulating electrode was placed in the 'bottle-neck' of the angular bundle, so as to maximally stimulate perforant path fibers¹⁶. After a 30 min interval, to allow for stabilization of the response, baseline data were collected by delivering subthreshold, low-frequency (0.1 Hz) test pulses. Computer averaging of waveforms, EPSP slope measurement, and the construction of voltage response curves were done as previously described¹⁵. Drugs were ejected by micro-pressure pulses (5–10 psi, 20 ms) to yield an ejected volume of 0.74 μ l (192 pmol) of APV. Eight trains of high-frequency stimulation (HFS: 400 Hz, 8 pulses/train, 0.4 ms pulse width, inter-train interval = 30 s) were used to induce LTP.

Five groups of animals received one of the following treatments: APV immediately prior to HFS (APV-preHFS), APV immediately after HFS (APV-postHFS), Tris carrier solution immediately prior to HFS (Tris-preHFS), APV applied with no HFS (APV), and Tris applied with no HFS (Tris). Responses were monitored with low-frequency test pulses for 60 min, following which the brain was rapidly frozen in situ. A 2 mm thick transverse section of dorsal hippocampus surrounding the recording electrode track was dissected in the cold room (4 °C), ho-

mogenized, and separated into aliquots for the in vitro phosphorylation reaction and subsequent autoradiography.

In agreement with previous reports^{5,10}, APV ejection blocked the initiation of LTP when applied before, but not after HFS. APV ejected after HFS also had no effect on the time-course of the potentiated response over the 60 min monitoring period. Ejections of APV or Tris in the absence of HFS had no observable effect on baseline synaptic transmission (Fig. 1).

Densitometric analysis of phosphoprotein autoradiograms revealed that protein F1 was increased in its in vitro phosphorylation measured 60 min after successful initiation of LTP*. No significant alterations (all $P > 0.25$ by one-way ANOVA) were seen in the phosphorylation of bands D1 (77 kDa), D2 (75 kDa), E1 (61 kDa), E2 (56 kDa), E3 (54 kDa), and F2 (42 kDa). This specificity is consistent with previous reports from this¹⁷ and other²⁰ laboratories. A one-way ANOVA test performed across all 5 groups revealed a significant effect of treatment on protein F1 phosphorylation ($F = 41.89$, $df = 3, 27$, $P < 0.001$; see Fig. 2A). Pairwise comparisons showed significant increases in protein F1 phosphorylation between the successfully potentiated groups (Tris-preHFS, APV-postHFS) and the non-potentiated groups (APV-preHFS, APV, Tris). This result is further illustrated by a significant positive correlation between protein F1 phosphorylation and the amplitude of the synaptic response measured immediately before sacrifice as tested by the point biserial correlation which compensates for clustering of the data into potentiated and non-potentiated groups ($r_{pb} = +0.912$, $df = 27$, $P < 0.001$ by two-tailed test; see Fig. 2B). Thus, application of APV prior to HFS

* Does an increase in protein phosphorylation measured in vitro reflect an increase in endogenous kinase activity? To address this question, tissue from LTP and control animals was homogenized and boiled for 5 min to destroy endogenous enzyme activity. The samples were then divided into two aliquots: one was treated with a saturating dose of alkaline phosphatase (AP) to remove all endogenously bound phosphate, following which the AP activity was destroyed by repeated freezing and thawing, and the other received no alkaline phosphatase treatment. Both aliquots were then reacted with an excess of purified exogenous PKC and [γ -³²P] ATP to phosphorylate all available sites and the reacted protein was then quantified by SDS-PAGE autoradiography. Thus, the incorporated ³²P in the AP_{treated} sample is a measure of total phosphorylation sites, and the value

$$\frac{AP_{treated} - AP_{untreated}}{AP_{treated}} \times 100$$

is a measure of the % of endogenously occupied phosphorylation sites. Tissue from LTP animals was significantly higher than that from control animals in this latter measure, indicating that the increase in phosphorylation of protein F1 measured in vitro is, at least in part, a consequence of increased endogenous kinase activity²¹.

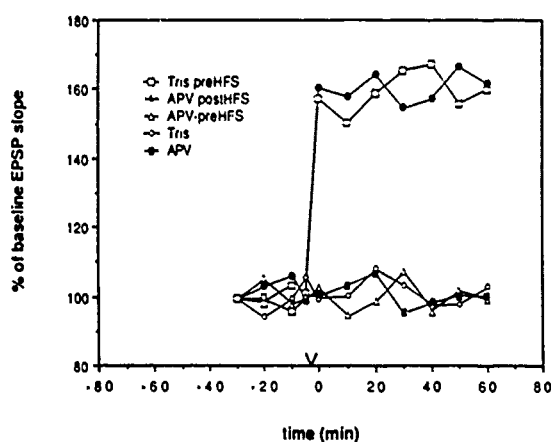


Fig. 1. Long-term potentiation of the perforant path, with drug ejection in the dentate gyrus molecular layer. Multi-barrelled micropipettes were placed in the perforant path terminal zone to record the local, negative-going population EPSP evoked by perforant path stimulation. Experiments were performed on male Sprague-Dawley rats, 150–200 g anesthetized with urethane. APV was dissolved in 20 mM Tris, which served as the carrier solution for control ejections. Ejection of the drug required 2–3 min, and the amount ejected was monitored by direct microscopic observation of the fluid meniscus within the drug-containing barrel. High-frequency stimulation to induce LTP was applied at $t = -5$ min (arrowhead in figure) for the groups APV-preHFS, APV-postHFS, and Tris-preHFS. The APV-postHFS group received APV at $t = 0$ while all other groups APV-preHFS, APV-postHFS, and Tris-preHFS. The APV-postHFS group received APV at $t = 0$ while all other groups received drug ejections at $t = -8$. The successfully potentiated groups, APV-postHFS and Tris-postHFS, show responses that do not decay over the 60 min monitoring period following HFS. $n = 6$ for all groups except APV-preHFS, where $n = 5$.

blocks both the initiation of LTP and the associated increase in protein F1 phosphorylation. The observation that application of APV after HFS failed to block this LTP-associated increase suggests that APV is acting *in vivo* rather than having a lingering effect *in vitro* during the phosphorylation reaction.

The tissue concentration within the hippocampus of the 192 pmol of APV applied *in vivo* is difficult to determine. However, if one assumes that the APV ejected (0.74 μ l of 260 μ M solution) diffuses homogeneously in 5 μ l of hippocampal tissue, then a rough estimate of 38 μ M concentration emerges. Could concentrations of APV of this order of magnitude be inhibiting PKC directly? We measured the activity of purified PKC *in vitro* as the difference in 32 P incorporation into lysine-rich histone in the presence and absence of phosphatidylserine²¹. When this assay was conducted in the presence of 5 μ M, 50 μ M, 500

μ M and 5 mM APV, PKC activity was reduced to 99%, 97%, 94% and 86% of baseline, respectively, indicating that APV did not directly inhibit PKC in the concentration applied.

The present results suggest that the LTP-associated increase in protein F1 phosphorylation is a consequence of an NMDA receptor-dependent initiation process. This observation is important in that it provides a link between initiation and maintenance of LTP. These processes may occur at specific synaptic locations.

It has been proposed that the trigger for LTP is located postsynaptically^{3,24,27}. In this model, the signal for initiation is a large, sustained, subthreshold depolarization of the postsynaptic membrane which relieves a voltage-dependent blockade of the NMDA receptor-associated channel by magnesium ions. This results in a sustained influx of cations into the postsynaptic cell. This proposal has been supported by the observations that APV will not block low-frequency synaptic transmission, and that the NMDA-receptor mediated component of low-frequency synaptic transmission may be observed only when physiological levels of extracellular magnesium are removed¹¹. In addition, LTP may be initiated by depolarization of the postsynaptic cell coupled with low-frequency stimulation of afferent fibers^{8,13,25}, and initiation of LTP by high-frequency stimulation may be blocked by hyperpolarization of the postsynaptic cell¹³. This notion, that integration of depolarization in the postsynaptic cell provides the trigger for LTP, is consistent with the observation that simultaneous activation of many afferent fibers, cooperativity of co-active afferents, is required for LTP initiation²⁰.

There is evidence suggesting that LTP response maintenance is mediated by alterations of the presynaptic terminal. For example, release of the putative neurotransmitter glutamate is persistently increased following LTP⁶. Interestingly, this increase in glutamate release may be blocked by application of APV prior to HFS, though APV does not alter basal glutamate release evoked by low-frequency stimulation⁷. It has been observed that glutamate release from control synaptosomes can be stimulated by a PKC activator, but glutamate release from synaptosomes prepared from potentiated animals cannot be further stimulated by a PKC activator¹⁹. This has led to the suggestion that PKC activation may be involved in

the control of glutamate release¹⁹, and is consistent with proposals from our laboratory that PKC activation/protein F1 phosphorylation is critical for maintenance of the LTP response²³, and that this maintenance is mediated by alterations of the presynaptic terminal²². Recent evidence that PKC in the perforant path/dentate gyrus granule cell synapses is localized presynaptically also supports this view²⁴. It should be noted that a model restricted to presynaptic alterations of PKC may not hold for all synapses of the hippocampus. PKC does not appear to be localized exclusively to the presynaptic side of either the mossy-fiber/CA3 cell synapse or the Schaffer collateral/CA1 cell synapse²⁸, and a recent report has demonstrated 'LTP-like' increases in excitability following injection of PKC into CA1 cells¹².

In summary, there is evidence that LTP is initiated postsynaptically through an NMDA-receptor-dependent process (although this does not appear to be the case in area CA3 of the hippocampus where NMDA receptors are very sparse⁹). There is also evidence that LTP is maintained, at least in part, through an

increase in glutamate release that may be dependent upon PKC activation/protein F1 phosphorylation. The present result, that blockade of NMDA receptors prevents LTP-associated protein F1 phosphorylation, suggests that this increase in protein F1 phosphorylation is a consequence of postsynaptic initiation processes. In such a case, a signal which travels from the postsynaptic membrane to the presynaptic terminal must be hypothesized⁷. However, it should be noted that presynaptic NMDA receptors are thought to exist^{5,7}. Consequently, it is possible that postsynaptic initiation and a presynaptic component of maintenance dependent on protein F1 phosphorylation are triggered in parallel, both in an NMDA receptor-dependent manner.

The micropressure injection unit was designed by Dr. J. Feldman and Dr. D. McCrimmon. Thanks to C. Haskell and M. Whitely for skillful technical assistance, and to P. Colley, D. Lovinger, S. Chan, and K. Murakami for helpful discussion. This work was

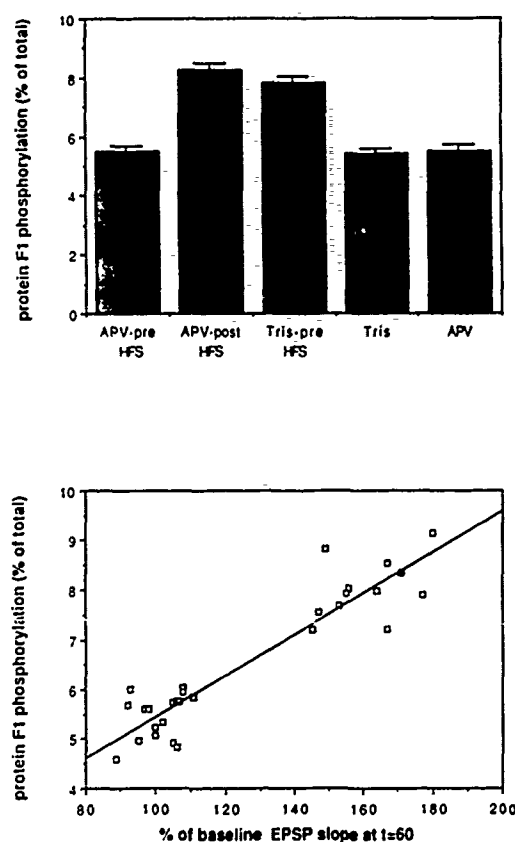


Fig. 2. Protein F1 phosphorylation measured in vitro following successful and unsuccessful LTP induction. The dorsal hippocampus was dissected in the cold room (4 °C) and homogenized with 40 vols. of buffer (50 mM Tris, 1.0 mM EDTA, 1.0 mM EGTA, 2 mM DTT, 10 μ g/ml leupeptin, pH 7.5 at 4 °C) in a custom-made plastic homogenizer. Protein concentration was adjusted to 1 mg/ml with 50 mM Tris. Aliquots of homogenate containing 50 μ g of protein were pre-incubated for 1 min at 30 °C in a solution containing 100 μ g/ml phosphatidylserine, 2.5 mM Mg^{2+} , and 200 μ M Ca^{2+} . The phosphorylation reaction was initiated by addition of [γ -³²P]-ATP (final concentration 5 μ M), and was stopped after 2 min by addition of 25 μ l of a solution containing 15% SDS, 10% β -mercaptoethanol, 30% sucrose, 0.05% Bromophenol blue, and 25 mM EDTA in 0.186 M Tris. The samples were boiled for 5 min and 70 μ l of reacted homogenate was layered onto 10% SDS-polyacrylamide gels for electrophoretic separation. The gels were stained with Coomassie brilliant blue, dried, and subjected to autoradiography using Kodak X-ray film. Autoradiographs were quantified by digitizing the output of a microdensitometer and integrating the area under each peak; phosphorylation was expressed as a percentage of the total densitometric area. The following results were replicated in three separate experiments. A: protein F1 phosphoproteins are significantly higher in the groups in which LTP was successfully initiated as determined by one-way ANOVA tests among the following pairs of groups: APV-preHFS/APV-postHFS ($F = 79.25$, $df = 1,9$, $P < 0.001$), APV-postHFS/APV ($F = 45.76$, $df = 1,10$, $P < 0.001$), Tris-preHFS/Tris ($F = 65.97$, $df = 1,10$, $P < 0.001$). B: protein F1 phosphorylation is positively correlated with the amplitude of the potentiated response (measured as % of baseline population EPSP) at $t = 60$, immediately before the animal was sacrificed ($r_{ph} = +0.912$, $df = 27$, $P < 0.001$).

supported by grants from the National Institutes of Health (MH 25281-13) and the Air Force (AFOSR

87-0042). D.J.L. is an Air Force Laboratory Graduate Fellowship recipient (S-789-000-001).

- 1 Akers, R.F., Lovinger, D.M., Colley, P.A., Linden, D.J. and Routtenberg, A., Translocation of protein kinase C (PKC) activity may mediate hippocampal long-term potentiation, *Science*, 231 (1986) 587-589.
- 2 Bliss, T.V.P. and Lomo, T., Long-lasting potentiation of synaptic transmission in the dentate area of the anesthetized rabbit following stimulation of the perforant path, *J. Physiol. (Lond.)*, 232 (1973) 331-356.
- 2a Chan, S., Colley, P. and Routtenberg, A., LTP-induced protein F1 phosphorylation in vitro: does it represent an increase or decrease in phosphate incorporation in vivo?, *Soc. Neurosci.*, in press.
- 3 Collingridge, G.L., Long-term potentiation in the hippocampus: mechanisms of initiation and modulation by neurotransmitters, *Trends Pharm. Sci.*, 6 (1985) 407-411.
- 4 Collingridge, G.L. and Bliss, T.V.P., NMDA receptors — their role in long-term potentiation, *Trends Neurosci.*, 10 (1987) 288-293.
- 5 Collingridge, G.L., Kehl, S.J., and McLennan, H., Excitatory amino acids in synaptic transmission in the schaffer collateral-commissural pathway of the rat hippocampus, *J. Physiol. (Lond.)*, 334 (1983) 33-46.
- 6 Dolphin, A.C., Errington, M.L., and Bliss, T.V.P., Long-term potentiation of the perforant path in vivo is associated with increased glutamate release, *Nature (Lond.)*, 297 (1982) 496-498.
- 7 Errington, M.L., Lynch, M.A. and Bliss, T.V.P., Long-term potentiation in the dentate gyrus: induction and increased glutamate release are blocked by D-(-)-amino-phosphonovalerate, *Neuroscience*, 20 (1987) 279-284.
- 8 Gustafsson, B., Wigstrom, H., Abraham, W.C. and Huang, Y.-Y., Long-term potentiation in the hippocampus using depolarizing current pulses as the conditioning stimulus to single volley synaptic potentials, *J. Neurosci.*, 7 (1987) 774-780.
- 9 Harris, E.W. and Cotman, C.W., Long-term potentiation of guinea-pig mossy-fiber responses is not blocked by N-methyl-D-aspartate antagonists, *Neurosci. Lett.*, 70 (1986) 132-137.
- 10 Harris, E.W., Ganong, A.H. and Cotman, C.W., Long-term potentiation in the hippocampus involves activation of N-methyl-D-aspartate receptors, *Brain Research*, 323 (1984) 132-137.
- 11 Herron, C.E., Lester, R.A.J., Coan, E.J. and Collingridge, G.L., Frequency-dependent involvement of NMDA receptors in the hippocampus: a novel synaptic mechanism, *Nature (Lond.)*, 322 (1986) 265-268.
- 12 Hu, G.-Y., Hvalby, O., Walaas, I., Albert, K.A., Skjeflo, P., Andersen, P. and Greengard, P., Protein kinase C injection into hippocampal pyramidal cells elicits features of long-term potentiation, *Nature (Lond.)*, 328 (1987) 426-429.
- 13 Kelso, S.R., Ganong, A.H. and Brown, T.H., Hebbian synapses in hippocampus, *Proc. Natl. Acad. Sci. U.S.A.*, 83 (1986) 5326-5330.
- 14 Linden, D.J., Murakami, K. and Routtenberg, A., A newly discovered protein kinase C activator (oleic acid) enhances long-term potentiation in the intact hippocampus, *Brain Research*, 379 (1986) 358-363.
- 15 Linden, D.J., Sheu, F.-S., Murakami, K. and Routtenberg, A., Enhancement of long-term potentiation by cis-unsaturated fatty acid: relation to protein kinase C and phospholipase A₂, *J. Neurosci.*, 7 (1987) 3783-3792.
- 16 Lomo, T., Patterns of activation in a monosynaptic cortical pathway: the perforant path input to the dentate area of the hippocampal formation, *Exp. Brain Res.*, 12 (1971) 18-45.
- 17 Lovinger, D.M., Colley, P.A., Akers, R.F., Nelson, R.B. and Routtenberg, A., Direct relation of long-term synaptic potentiation to phosphorylation of membrane protein F1, a substrate for membrane protein kinase C, *Brain Research*, 399 (1986) 205-211.
- 18 Lovinger, D.M., Wong, K., Murakami, K. and Routtenberg, A., Protein kinase C inhibitors eliminate hippocampal long-term potentiation, *Brain Research*, 436 (1987) 177-183.
- 19 Lynch, M.A. and Bliss, T.V.P., Long-term potentiation of synaptic transmission in the hippocampus of the rat: effect of calmodulin and oleoyl-acetyl-glycerol on release of [³H]-glutamate, *Neurosci. Lett.*, 65 (1986) 171-176.
- 20 McNaughton, B.L., Douglas, R.M. and Goddard, G.V., Synaptic enhancement in fascia dentata: cooperativity among coactive afferents, *Brain Research*, 157 (1978) 277-293.
- 21 Murakami, K., Chan, S.Y. and Routtenberg, A., Protein kinase C activation by cis-fatty acid in the absence of Ca²⁺ and phospholipids, *J. Biol. Chem.*, 261 (1986) 15424-15429.
- 22 Routtenberg, A., Protein kinase C activation leading to protein F1 phosphorylation may regulate synaptic plasticity by presynaptic terminal growth, *Behav. Neurol. Biol.*, 44 (1985) 186-200.
- 23 Routtenberg, A., Synaptic plasticity and protein kinase C, *Prog. Brain Res.*, 69 (1986) 211-234.
- 24 Routtenberg, A., Colley, P., Linden, D., Lovinger, D., Murakami, K. and Sheu, F.-S., Phorbol ester promotes growth of synaptic plasticity, *Brain Research*, 278 (1986) 374-378.
- 25 Sastry, B.R., Goh, J.W. and Auyeung, A., Associative induction of post-tetanic and long-term potentiation in CA1 neurons of rat hippocampus, *Science*, 232 (1986) 988-990.
- 26 Schrama, L.H., De Graan, P.N.E., Wadman, W.J., Lopes da Silva, F.H. and Gispen, W.W., Long-term potentiation and 4-aminopyridine-induced changes in protein and lipid phosphorylation in the hippocampal slice, *Prog. Brain Res.*, 69 (1986) 245-258.
- 27 Wigstrom, H. and Gustafsson, B., On long-lasting potentiation in the hippocampus, a proposed mechanism for its dependence on coincident pre- and post-synaptic activity, *Acta Physiol. Scand.*, 123 (1985) 519-522.
- 28 Worley, P.F., Baraban, J.M., De Souza, E.M. and Snyder, S.H., Mapping second messenger systems in the brain: differential localizations of adenylate cyclase and protein kinase C, *Proc. Natl. Acad. Sci. U.S.A.*, 83 (1986) 4053-4057.

The Two Major Phosphoproteins in Growth Cones Are Probably Identical to Two Protein Kinase C Substrates Correlated with Persistence of Long-Term Potentiation

Robert B. Nelson,^{1,*} David J. Linden,¹ Carolyn Hyman,² Karl H. Pfenninger,³ and Aryeh Routtenberg,¹

¹Cresap Neuroscience Laboratory, Northwestern University, Evanston, Illinois 60201, ²Department of Cellular Biology, New York University Medical Center, New York, New York 10016, and ³Department of Cellular and Structural Biology, University of Colorado, Denver, Colorado 80262

Regulation of neural protein kinase C (PKC) activity appears to directly affect the persistence of long-term potentiation (LTP; Akers and Routtenberg, 1985; Lovinger et al., 1985, 1986, 1987; Routtenberg et al., 1985, 1986; Akers et al., 1986; Linden et al., 1987), a model of neural plasticity (Bliss and Lomo, 1973). In addition, the *in vitro* phosphorylation of a brain-specific PKC substrate, protein F1 (*M*, 47 kDa, pI 4.5), has been directly correlated with persistence of LTP (Lovinger et al., 1986). Because PKC has been implicated in neurite outgrowth and is present at high levels in growth cone-rich areas of fetal brain, we investigated and characterized PKC substrates in a preparation of isolated nerve growth cone fragments from fetal rat brain and compared them with PKC substrates found in adult rat hippocampus. Four major proteins in the growth cone preparation showed endogenous phosphorylation levels at least 10-fold greater than any other phosphoproteins. Three of these 4 phosphoproteins, termed pp40, pp46, and pp80 (Katz et al., 1985), were phosphorylated by exogenous PKC in a dose-dependent manner, indicating that PKC activity might be of particular importance relative to other kinases in growth cone function. The 2 most highly labeled PKC substrates, pp46 and pp80, comigrated on 2-dimensional gels with the adult hippocampal proteins F1 and "80k" (*M*, 78–80 kDa, pI 4.0), respectively. In addition, similarities in charge heterogeneity, 2-dimensional phosphopeptide maps, and increased phosphorylation in the presence of exogenous PKC or PKC stimulators suggest that protein F1 and 80k are highly homologous to, if not identical to, pp46 and pp80, respectively. The relationship of 80k phosphorylation to persistence of LTP has been masked previously by its comigration on 1-dimensional SDS gels with the major phosphoproteins

synapsin Ia and Ib. Quantitative analysis of *in vitro* labeled phosphoproteins separated by 2-dimensional gel electrophoresis revealed that this second major neural PKC substrate, along with protein F1, was directly correlated with persistence of LTP induced *in vivo*. The present results suggest that PKC and its substrates play a central role in growth cone function and that this protein kinase system may underlie both normal neurite growth in developing brain and neural plasticity at adult synapses (Routtenberg, 1985, 1986; Pfenninger, 1986; Pfenninger et al., 1986).

Protein kinase C (PKC; Kikkawa et al., 1982), a Ca^{2+} and phospholipid-dependent kinase, appears to be translocated from a cytosolic to a membrane-associated state following the induction of long-term potentiation (LTP) in the intact hippocampus of adult rats (Akers et al., 1986). Recent evidence has suggested that PKC may directly regulate persistence of LTP: intrahippocampal injection of PKC stimulators, such as phorbol esters or oleic acid, increase the persistence of LTP (Routtenberg et al., 1986; Linden et al., 1987); conversely, the administration of the PKC inhibitors polymyxin B, melittin, or H-7 all block the maintenance of LTP (Lovinger et al., 1987).

PKC has also been linked to neural development: it copurifies with, and may be identical to, the phorbol ester receptor (Niedel et al., 1983) which has been found in high concentrations in growth cone-rich regions of the developing nervous system (Nagle et al., 1981; Murphy et al., 1983). Moreover, phorbol esters, which both activate and translocate PKC (Castagna et al., 1982; Kraft and Anderson, 1983), are able to induce neurite outgrowth in cultured explants (Hsu et al., 1984; Natyzak and Laskin, 1984).

Because we have previously found that the phosphorylation of a brain-specific PKC substrate, protein F1, is directly correlated with persistence of LTP in adult rats, we were interested in whether PKC might phosphorylate the same substrates in both adult hippocampus and in nerve growth cones from fetal rat brain. Substrates for Ca^{2+} -dependent kinases have been reported to be prominent in a purified fraction of "growth cone particles" (GCPs; Pfenninger et al., 1983; Katz et al., 1985; Hyman and Pfenninger, 1987). Using 2-dimensional gel electrophoresis and 2-dimensional phosphopeptide mapping, we compared the properties of phosphoproteins in a synaptosome-enriched fraction of adult hippocampal formation with those present in GCPs isolated by subcellular fractionation of fetal brain. Upon identifying 2 PKC substrates common to both

Received June 18, 1987; revised May 25, 1988; accepted June 3, 1988.

This research was supported by a grant from the National Institutes of Health (MH 25281-13 to A.R.), the National Science Foundation (BNS86-44972 to K.H.P.), and the Air Force (AFS087-0042 to A.R.). R.B.N. is a National Research Service Award recipient (1 F31 DAO5254). D.J.L. is an Air Force Laboratory Graduate Fellowship recipient (S-789-000-001), and C.H. is the recipient of a Muscular Dystrophy Association postdoctoral fellowship. We wish to thank Dr. Shew Chan for providing purified protein F1 and Dr. Kentaro Murakami for providing purified protein kinase C.

Correspondence should be addressed to Aryeh Routtenberg, Northwestern University, Cresap Neuroscience Laboratory, 2021 Shendan Road, Room 311, Evanston, IL 60208.

* Present address: The DuPont Company, Neuroscience Group, Experimental Station, E400/3442, Wilmington, DE 19898.

Copyright © 1989 Society for Neuroscience 0270-6474/89/020381-09\$02.00/0

GCPs and adult hippocampal formation, we used quantitative analysis of 2-dimensional gels to correlate the endogenous phosphorylation of these PKC substrates in adult hippocampus with the persistence of LTP.

Materials and Methods

Materials. All chemicals were analytical grade. Ultrapure urea was purchased from Schwarz-Mann. Tris (hydroxymethyl) aminomethane, acrylamide, and methylene bisacrylamide were from Polysciences. γ - 32 P-ATP was obtained from ICN. Phosphatidylserine (PS) and protein standards for SDS-PAGE were supplied by Sigma. *Staphylococcus aureus* V8 protease was obtained from Miles Laboratories. Ampholytes, 40%, of pH 3–10 were from Bio-Rad. Purified PKC and purified protein F1 were prepared as described previously (Murakami and Routtenberg, 1985; Chan et al., 1985).

Growth cone particles. GCPs were prepared as described previously (Pfenninger et al., 1983). Briefly, a low-speed supernatant from homogenate of 17-d gestation rat brain was layered onto a discontinuous sucrose gradient and spun to equilibrium ($248,000 \times g_{\text{max}}$ for 40 min, 4°C). The band at the load/0.75 M sucrose interface was collected, diluted, and centrifuged at $39,000 \times g_{\text{max}}$. This pellet (P_1), consisting of mostly broken GCPs, was resuspended in 50 mM Tris-HCl (pH 8.1).

Adult brain synaptosome-enriched fraction. A synaptosome-enriched fraction (P_2) was prepared as described previously (Conway and Routtenberg, 1978). Briefly, rat hippocampal formation was homogenized in 0.32 M sucrose and centrifuged at $1000 \times g_{\text{max}}$ for 10 min. The supernatant was centrifuged a second time at $1000 \times g_{\text{max}}$, and the second pellet also discarded. The second supernatant was centrifuged at $10,000 \times g_{\text{max}}$ for 20 min, and the resulting pellet was washed by resuspension in 0.32 M sucrose and centrifugation at $10,000 \times g_{\text{max}}$ for 20 min. This final pellet (P_2) was resuspended in buffers indicated in the individual figure captions.

Phosphorylation of tissue fractions in vitro. After protein determination (Lowry et al., 1951), all GCP, adult P_2 , or adult homogenate samples were adjusted to 2 mg/ml protein. Buffer containing all ions, chelating agents, and test substances for the final reaction conditions was added to each sample while on dry ice. In the case of experiments with PS or PKC, experimental and control samples were thawed on ice for 10 min in the presence of various concentrations of Triton X-100 (TX-100). To measure endogenous phosphorylation, samples were preincubated at 30°C for 45 sec, followed by incubation with $5 \mu\text{M}$ γ - 32 P-ATP for 15 sec in a final volume of 40 μl . Final reaction conditions are stated in text and figure captions. Quenching was by liquid nitrogen, followed by addition of 8.5 M urea, 0.5% TX-100 (vol/vol), and 3% β -mercaptoethanol (vol/vol) for 2-dimensional separation. For separation by 1-dimensional Laemmli gels (5–15% acrylamide), samples were quenched by addition of 3 \times Laemmli sample buffer containing SDS (Laemmli, 1970). The resulting autoradiographs were analyzed by microdensitometry and computer integration of densitometric peaks (R. B. Nelson, D. J. Linden, and A. Routtenberg, unpublished observations).

Analysis by 2-dimensional gel electrophoresis (IEF-SDS). Two-dimensional electrophoresis by isoelectric focusing (IEF) and SDS molecular mass separation was performed according to O'Farrell (1975) with modifications described previously (Nelson and Routtenberg, 1985). Ten percent (wt/vol) polyacrylamide gels were used to separate protein in the second dimension, and in some cases gels were stained using a modification of the silver stain of Merrill et al. (1981). Gels were dried and analyzed by autoradiography as described previously (Mitrius et al., 1981).

Levels of protein phosphorylation were determined by locating the proteins autoradiographically in the gels, excising the spots or bands, and counting directly without elution in a liquid scintillation spectrometer.

Analysis by nonequilibrium pH gradient 2-dimensional gel electrophoresis (NEPHGE-SDS). The procedure for NEPHGE-SDS was essentially the same as that described by O'Farrell et al. (1977) with modifications described previously (Nelson and Routtenberg, 1985). Proteins were excised from NEPHGE-SDS gels and counted for ^{32}P -incorporation as described in detail elsewhere (Nelson et al., 1987).

One-dimensional peptide mapping. Limited proteolysis using *Staphylococcus aureus* V8 protease was performed using a modification of the method of Cleveland et al. (1977). Briefly, proteins from dried,

unstained 2-dimensional gels were located by autoradiography, excised, swollen in equilibration buffer, and loaded on a 15% acrylamide (wt/vol) SDS-PAGE gel with a 3% acrylamide stacking gel 1 cm in length. Excised protein slices were overlaid with 10 μg *S. aureus* V8 protease in a 10 μl volume. Gels were electrophoresed at 50 V for 1 hr (at which point the bromophenol blue tracking dye had entered the resolving gel), then at 160 V until the tracking dye reached the bottom of the gel. Electrophoresis was not interrupted at the stacking/resolving gel interface. Gels were then stained, dried, and processed for autoradiography.

Two-dimensional peptide mapping. An alternate procedure for limited proteolysis of proteins using *S. aureus* V8 protease, also derived from Cleveland et al. (1977), was used to prepare peptide fragments for separation by NEPHGE-SDS. Briefly, labeled protein spots containing F1 or pp46 from 2-dimensional gels were pooled, hydrated, macerated with a Teflon pestle, and eluted in distilled water for 24 hr at 37°C . The protein-containing supernatant was filtered, lyophilized, and resuspended in 334 μl 20 $\mu\text{g/ml}$ BSA added as carrier, then protein was precipitated by adding 60% TCA to a 20% final concentration (wt/vol). After washing twice with 1:2 ethanol/ether, the precipitate was resuspended in 0.125 M Tris-HCl, pH 7.2, 10% glycerol, and 0.5% SDS, then incubated 1.5 hr at 37°C in the presence of 0.2 mg/ml V8 protease. After the reaction for 2-dimensional analysis was stopped as described above, peptide fragments were separated in 2 dimensions by use of 20% acrylamide/2 mg/ml bis-acrylamide resolving gel in the second dimension. Gels were processed for autoradiography as described above.

In vivo long-term potentiation. The procedure for inducing LTP is described in detail elsewhere (Lovinger et al., 1986). Briefly, anesthetized animals were stimulated in the perforant path using 8 trains of eight 400 Hz pulses. The extracellular population spike was recorded from the hilus of the dentate gyrus 3 and 13 min following the high-frequency stimulation; the brains were then rapidly frozen in liquid nitrogen and stored at -20°C .

The magnitude of spike potentiation (percentage of baseline spike amplitude, % BSA) was calculated using the following formula:

$$(\text{Spike amplitude after high-frequency stimulation at } t_2 / \text{Spike amplitude before high-frequency stimulation}) \times 100,$$

where $t_2 = 3$ or 13 min.

The persistence of spike potentiation was calculated as

$$(\% \text{ BSA at } t_2 - 100) / (\% \text{ BSA at } t_1 - 100),$$

where t_1 and t_2 refer to 3 and 13 min, respectively, following delivery of high-frequency stimulation.

Results

Proteins from a P_2 fraction of adult rat hippocampal formation and from a GCP fraction were phosphorylated *in vitro* using γ - ^{32}P -ATP and separated in parallel by NEPHGE-SDS to compare endogenously labeled phosphoproteins in the 2 preparations (Fig. 1). As reported previously, there are striking differences in the relative incorporation of phosphoproteins between these 2 preparations (Katz et al., 1985). In GCPs, only 4 major phosphoproteins were detectable, in contrast to 20 or more in adult P_2 . Although many other phosphoproteins were detectable on longer exposure of the GCP autoradiographs, their incorporation was at least 10-fold lower than that of the 4 major phosphoproteins. The most highly labeled phosphoprotein was pp46 (#3), followed in order by pp80 (#2), pp40 (#4), and a grouping of proteins that might correspond to phosphorylated tubulin.* Note that synapsin Ia and Ib (#1), among the most prominent phosphoproteins in adult P_2 , are only minor components in GCPs (Katz et al., 1985).

In order to identify PKC substrates in adult P_2 and GCPs, we added exogenous, purified PKC to the 2 preparations in the

* The fourth major phosphoprotein(s) on the 2-dimensional gels are probably α and β -tubulin based on their molecular mass, isoelectric point, and partial insolubility (manifested as "streaking") on the gels.

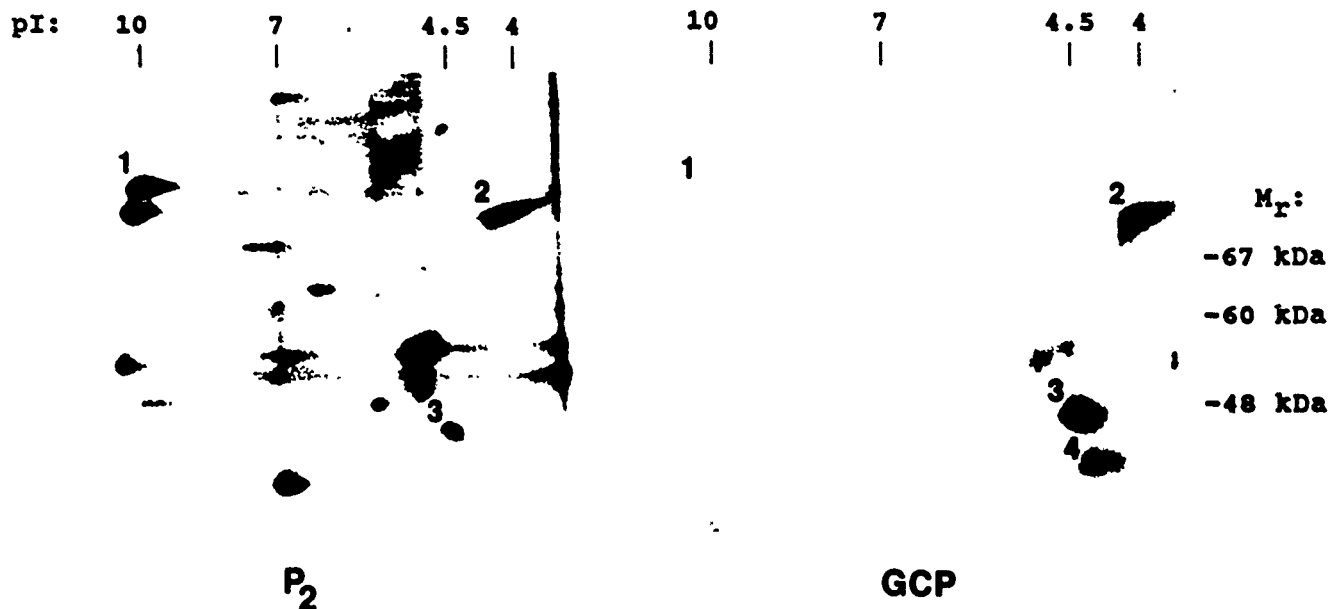


Figure 1. Autoradiographs comparing ^{32}P -labeled phosphoproteins from P_2 and GCPs. Phosphoproteins from a P_2 fraction of adult rat hippocampal formation and from GCPs were separated by NEPHGE-SDS (see Materials and Methods). Samples were reacted with $\gamma\text{-}^{32}\text{P}\text{-ATP}$ (see Materials and Methods). Final reaction volume was $40\ \mu\text{l}$ containing $1\ \text{mg/ml}$ protein in $50\ \text{mM}$ Tris-HCl ($\text{pH}\ 7.1$), $10\ \mu\text{M}$ free CaCl_2 , and $1\ \text{mM}$ free MgCl_2 buffered with $1\ \text{mM}$ EDTA. Visible characterized proteins believed to correspond between the 2 preparations are (1) synapsin Ia/Ib (Ueda and Greengard, 1977; Nestler and Greengard, 1986), which are clearly seen only upon longer exposure in GCPs; (2) 80k in adult P_2 and pp80 in GCPs (Wu et al., 1982; Katz et al., 1985; Blackshear et al., 1986); (3) protein F1 in adult P_2 and pp46 in GCPs; (4) pp40 in GCPs (Katz et al., 1985), normally barely detectable in adult preparations. Autoradiographs were exposed for different times to give comparable development of the PKC substrates (number 2, 3, and 4) in each autoradiograph. Protein 4 labeling (pp40) was not detectable among P_2 proteins even on longer exposure of the autoradiograph. Baseline cpm values for proteins were as follows: F1, 3241; pp46, 59995; 80k, 9619; pp80, 51782. Autoradiographs are representative of several comparisons.

presence of $300\ \mu\text{M}$ Ca^{2+} . We found a dose-dependent increase in phosphorylation of pp46, pp80, and pp40 in GCPs (Table 1). Thus, 3 of the 4 major phosphoproteins detected in GCPs were PKC substrates. In the adult hippocampal P_2 fraction, PKC

stimulated the phosphorylation of 2 proteins termed protein F1 and 80k, but this stimulation was limited and did not increase steadily with increasing PKC concentration (Table 1). A factor in adult rat brain that inhibits PKC activity has recently been discovered (Chan et al., 1985). Since this inhibitory factor is removed by ammonium sulfate precipitation (Chan et al., 1985), we prepared such an inhibitor-free fraction from rat brain P_2 ,

* Maximal activation rate of purified PKC phosphorylating purified protein in F1 occurs at a concentration near $200\ \mu\text{M}$ Ca^{2+} and $100\ \mu\text{g/ml}$ PS (Chan et al., 1986).

Table 1. Stimulation of ^{32}P incorporation into selected proteins by exogenous purified PKC

Added PKC (pmol/min)	F1 from P_2	80k from P_2	F1 from ASP 40-80	80k from ASP 40-80	pp46 from GCPs	pp80 from GCPs	pp40 from GCPs
0	100	100	100	ND	100	100	100
1	111	60	193	ND	133	168	147
5	102	67	592	100	150	233	224
10	101	107	1139	375	297	344	361
50	155	226	3777	933	619	898	917
100	154	384	6696	2487	818	1432	1479

^{32}P incorporation into proteins was measured by liquid scintillation spectrometry of protein spots cut from 2-dimensional gels (see Materials and Methods). Stimulation of incorporation by added PKC is expressed as a percentage of control values. ND, not detectable above background. PKC activity is expressed as picomoles P_i incorporated into histone per minute (pmol/min). Final reaction concentrations were $1\ \text{mg/ml}$ protein in $50\ \text{mM}$ Tris-HCl ($\text{pH}\ 7.1$), 0.1% TX-100, $300\ \mu\text{M}$ Ca^{2+} free, $1\ \text{mM}$ Mg^{2+} free, buffered with $1\ \text{mM}$ EDTA. Incubation with $5\ \mu\text{M}$ $\gamma\text{-}^{32}\text{P}\text{-ATP}$ was as described in Figure 1. Purified PKC having a specific activity of $1460\ \text{nmol}\ \text{P}_i/\text{min}\ \text{mg}$ histone was prepared as previously described (Murakami and Routtenberg, 1985). "F1 from P_2 " and "80k from P_2 " were both cut from the same 2-dimensional gels of P_2 proteins. ASP 40-80 was a 1-step purification of F1 from a pH extract of P_2 proteins by 40 and 80% ammonium sulfate precipitation followed by dialysis against $50\ \text{mM}$ Tris-HCl ($\text{pH}\ 7.1$). This fraction was then phosphorylated under the conditions listed above with the inclusion of $50\ \mu\text{g/ml}$ of PS and separated on 2-dimensional gels. Phosphorylation of 80k protein was detectable in this fraction after a minimal addition of $5\ \text{pmol/min}$ of PKC activity. This level of phosphorylation was then used as a baseline for addition of higher PKC concentrations. "pp46 from GCPs," "pp80 from GCPs," and "pp40 from GCPs" were all cut from the same 2-dimensional separations of phosphorylated GCP proteins. Experiments were performed twice. Values shown are from one experiment.

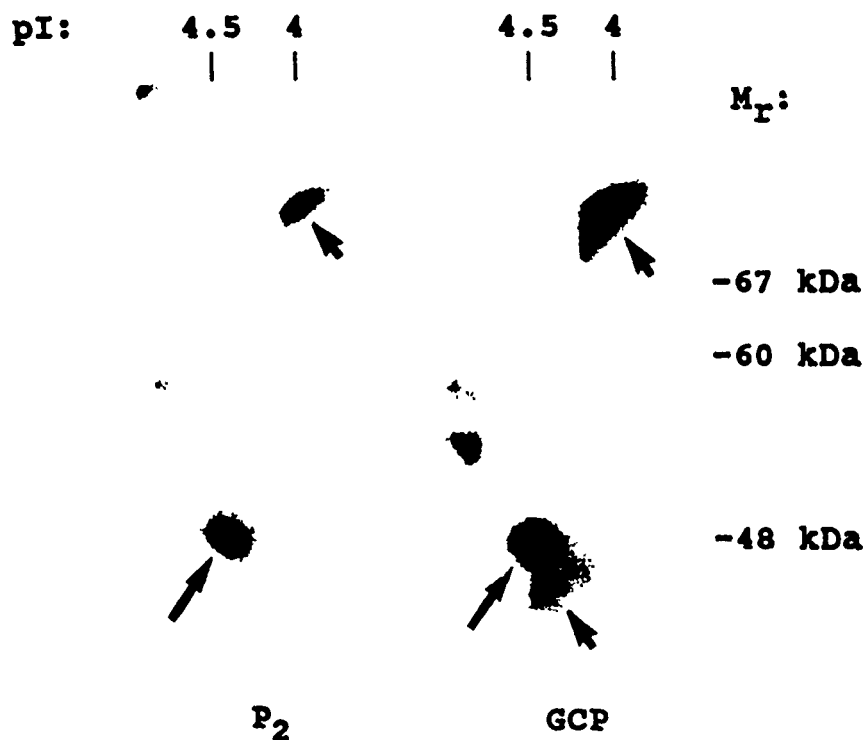


Figure 2. Comigration and similar microheterogeneity on 2-dimensional autoradiographs of phosphorylated protein F1 versus pp46, and 80k versus pp80. Proteins adjusted to 1 mg/ml concentration were labeled by endogenous phosphorylation as in Figure 1 and separated by IEF-SDS (see Materials and Methods). Protein F1 in P_2 and pp46 in GCPs are indicated by *arrows*. 80k in P_2 , pp80 and pp40 in GCPs are indicated by *arrowheads*. The exposure times of the autoradiographs were adjusted to give similar intensities of protein F1 and pp46. Baseline cpm values for proteins were as follows: F1, 2197; pp46, 33005; 80k, 1641; pp80, 30294. Autoradiographs are representative of several comparisons.

then added increasing concentrations of PKC to the fraction in the presence of 50 μ g/ml PS. In this preparation, a dose-dependent stimulation of protein F1 and 80k phosphorylation by exogenous, purified PKC was found (Table 1). The large percentage increase in phosphorylation obtained following addition of PKC to this fraction is partly due to removal of most of the endogenous PKC activity following ammonium sulfate precipitation, so that basal phosphorylation of protein F1 and 80k is extremely low.

Whereas a protein potentially corresponding to pp40 was detectable only on prolonged exposure in the adult P_2 preparation, 2 relatively well-labeled phosphoproteins termed protein F1 and 80k in adult rat brain comigrated with the GCP phosphoproteins termed pp46 and pp80, respectively (Fig. 2). Under the gel conditions used, protein F1 and pp46 exhibited an apparent molecular mass of 47 kDa* and an isoelectric point of 4.5. Both proteins also exhibited a slight, but characteristic charge heterogeneity, with a slightly higher molecular mass at the alkaline end. This microheterogeneity is more apparent in silver stains of protein F1 and pp46 (Fig. 3); 80k and pp80 had an apparent molecular mass of 78–80 kDa and an isoelectric point of 4.0. These 2 proteins shared a distinctive charge heterogeneity with a higher molecular weight at the acidic end and a "trail" of label in the molecular mass dimension at the alkaline end. This distinctive microheterogeneity is also apparent in the silver stain of pp80 in Figure 3; however, 80k was not detectable in the silver stain. Because equal amounts of protein were loaded onto the gels shown in Figure 3, the relative stain densities of proteins

indicate qualitative enrichment of pp46 and pp80 in GCPs versus protein F1 and 80k in P_2 .

The 4 phosphoproteins were further compared by subjecting each to peptide mapping following limited proteolysis with *S. aureus* V8 protease (Fig. 4). On a 1-dimensional separation, 3 phosphopeptide bands were generated under these conditions from protein F1 and pp46: 2 major bands at 11 and 13 kDa, and a minor band at 23 kDa. When these same proteolytic fragments were further compared by separation in 2 dimensions, an extensive heterogeneity was revealed within the 11 and 13 kDa bands of both proteins, while the 23 kDa band appeared as a single acidic peptide. On 2-dimensional peptide maps, protein F1 and pp46 have at least 10 phosphopeptide spots in common. Protein F1 and pp46 thus appear to be highly homologous, if not identical, on the basis of these maps.⁷

Two-dimensional phosphopeptide maps of 80k and pp80 yielded 2 bands of peptides at 12 and 14 kDa (Fig. 4). In contrast to protein F1 and pp46, the pattern on these maps was 3 closely spaced, poorly resolved peptides of basic pH within each band. An aberration in the migration front of these peptides was seen in the area of highest label incorporation. This aberration was reproducible and appears to be due to some property inherent in the peptides that disturbs their migration on SDS gels.⁸ 80k and pp80 appear to be highly similar, if not identical, on the basis of these maps.

* Observations from several laboratories, including our own, indicate that F1/pp46 migrates anomalously on SDS-PAGE gels with regard to molecular mass standards. The apparent molecular mass of F1/pp46 decreases with increasing percentage polyacrylamide gels. Thus, it was important in the present study to compare protein F1 and pp46 separated in parallel on the same gel system.

⁷ Small differences in the phosphopeptide pattern on these maps (particularly in minor phosphopeptides) appears to be due to minor differences in the degree of proteolysis rather than differences in substrate cleavage sites since these minor differences are not consistent. In side experiments to explore this issue, we performed parallel digestions on identical proteins from the same preparation and still obtained minor differences in phosphopeptide patterns.

⁸ Recent evidence suggests that 80k/pp80 (and pp40) both covalently bind fatty acids (Perrone-Bizzozero et al., 1987). Charge masking by fatty acids might explain both the poor resolution of 80k/pp80 peptide fragments in the isoelectrofocusing dimension and the characteristic aberration produced in the migration front of the SDS dimension.

Because protein F1, pp46, 80k, and pp80 could be phosphorylated by exogenous PKC, we characterized the endogenous PKC activity in adult hippocampal P_2 and fetal brain GCPs. Under the same basal phosphorylation conditions (no addition of kinase stimulators) with protein adjusted to 1 mg/ml, the endogenous phosphorylation of pp46 and pp80 in GCPs was typically 15–20 times higher than that of protein F1 and 80k in adult hippocampal P_2 (measured as cpm of 32 P-incorporation into protein spots; see Figs. 1 and 2 legends). In contrast, overall kinase activity was lower in GCPs as measured by TCA precipitation of total protein, being 60% of the incorporation found in hippocampal P_2 . Although part of this increased phosphorylation of pp46 and pp80 in GCPs relative to protein F1 and 80k in P_2 would be due to the enrichment of these proteins in GCPs (Fig. 3), the short *in vitro* reaction time used favors detection of differences in kinase activity over differences in substrate concentration (Matus et al., 1980). It is therefore likely that the higher endogenous phosphorylation of pp46 and pp80 also represents higher activity of the kinase phosphorylating these proteins.

As expected for endogenous PKC activity, addition of PS stimulated the phosphorylation of both pp46 and protein F1 in a dose-dependent manner; however, PS was only moderately effective in increasing the phosphorylation of pp80 and 80k (Fig. 5). We have found 80k phosphorylation to be highly stimulated by PS in a synaptosomal cytosol fraction (R. B. Nelson and A. Routtenberg, unpublished observations), similar to Wu et al. (1982); however, these studies used soluble fractions separated from membrane, as did a report finding a large PS stimulation of pp80 (Katz et al., 1985). We have also previously seen PS inhibition of 80k phosphorylation in a membrane preparation under the same conditions that protein F1 phosphorylation was stimulated (a 0.05% TX-100-containing P_2 preparation; Nelson and Routtenberg, 1985). It appears, then, that the presence or absence of membrane elements, as well as the concentration of detergent added, is critical in determining relative stimulation of protein phosphorylation following addition of phospholipids. During the course of these experiments, we also discovered that the concentration of added detergent at which PS stimulation of protein F1 and pp46 is obtained is different between P_2 and GCPs. At a 0.05% final concentration of TX-100, for example, phosphorylation of pp46 was inhibited by added PS, while protein F1 phosphorylation was stimulated. This discrepancy most likely reflects differences in the lipid environment of GCPs versus P_2 since a high lipid-to-protein ratio has been found in GCP membranes (Sbaschnig-Agler et al., 1988).

The second major PKC substrate, 80k, described here in both adult P_2 and GCPs, is masked in adult P_2 by comigration on 1-dimensional gels with the major phosphoproteins synapsin Ia and Ib (see Fig. 1). In order to determine whether phosphorylation of 80k is also correlated with persistence of LTP (as previously reported for protein F1), we used 2-dimensional electrophoresis (NEPHGE-SDS) to separate 32 P-labeled dorsal hippocampal proteins from 17 animals receiving high-frequency stimulation and determined incorporation into protein spots by liquid scintillation. The phosphorylation of both protein F1 and 80k was directly correlated with persistence of LTP 13 min after the delivery of the potentiating stimulation (Fig. 6). When the same samples were separated on 1-dimensional gels by molecular mass alone, only the correlation of protein F1 to persistence of LTP was detected (data not shown), in agreement with previous reports (Routtenberg et al., 1985; Lovinger et al., 1986).

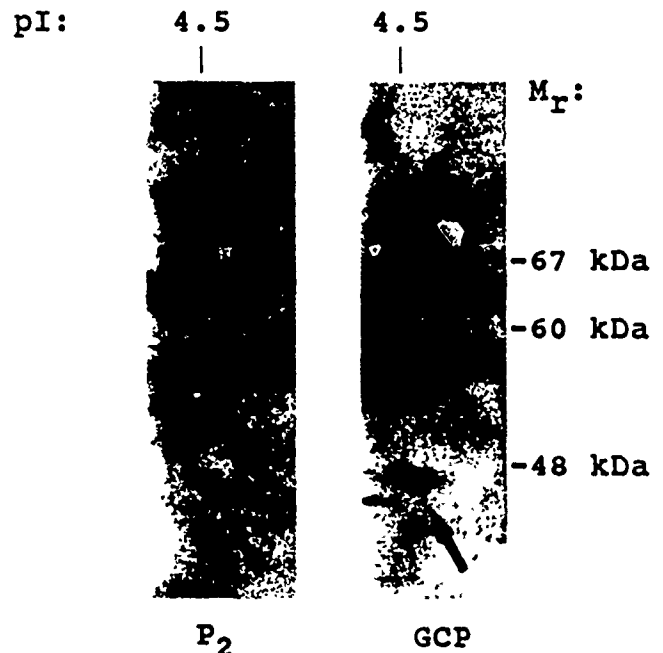


Figure 3. Enrichment of pp46 and pp80 in GCPs versus protein F1 and 80k in P_2 , and similar microheterogeneity in pp46 and protein F1 from 2-dimensional silver-stained gels. P_2 fraction and GCPs were separated by IEF-SDS as in Figure 2. Arrows indicate F1 in P_2 and pp46 in GCPs. Arrowhead indicates pp80 in GCPs. Staining of 80k in P_2 was below detection level. In both cases, 25 μ g of total protein was loaded on the gels. Gels were stained as described in Materials and Methods.

Discussion

Activity of PKC has been implicated in both neurite outgrowth and in the persistence of LTP. In the present report, PKC substrates were compared between a fraction of purified growth cone particles from fetal rat brain (GCPs) and a synaptosome-enriched fraction of hippocampal formation from adult rat brain. We detected 4 major phosphoproteins from GCPs having 32 P-incorporation levels at least 10-fold greater than other phosphoproteins in the GCP fraction (Fig. 1). Of these 4 phosphoproteins, the 3 termed pp80, pp46, and pp40 (Katz et al., 1985; Hyman and Pfenninger, 1987) were all phosphorylated by exogenously added PKC, suggesting that PKC plays a central role relative to other protein kinases in growth cone function. These 3 phosphoproteins also appear to be the same as the 3 major phorbol ester stimulated phosphoproteins in a primary neuronal cell culture (Burgess et al., 1986).

Although immunochemical and amino acid sequence data are presently available only for protein F1 (Rosenthal et al., 1987), the present evidence strongly suggests that pp46 and pp80, the 2 highest endogenously phosphorylated substrates detected in GCPs (Fig. 1), are identical to protein F1 and 80k, respectively, 2 acidic phosphoproteins in adult rat hippocampal formation. This identification is made on the basis of similar molecular mass, isoelectric point, charge heterogeneity, and 2-dimensional phosphopeptide mapping of these proteins when examined in parallel in the same gel system. In addition, both proteins in GCPs responded similarly to their counterparts in adult hippocampal P_2 with regard to phosphorylation by exogenous PKC and in their response to the addition of the endogenous PKC stimulators Ca^{2+} and PS. Increased phosphor-

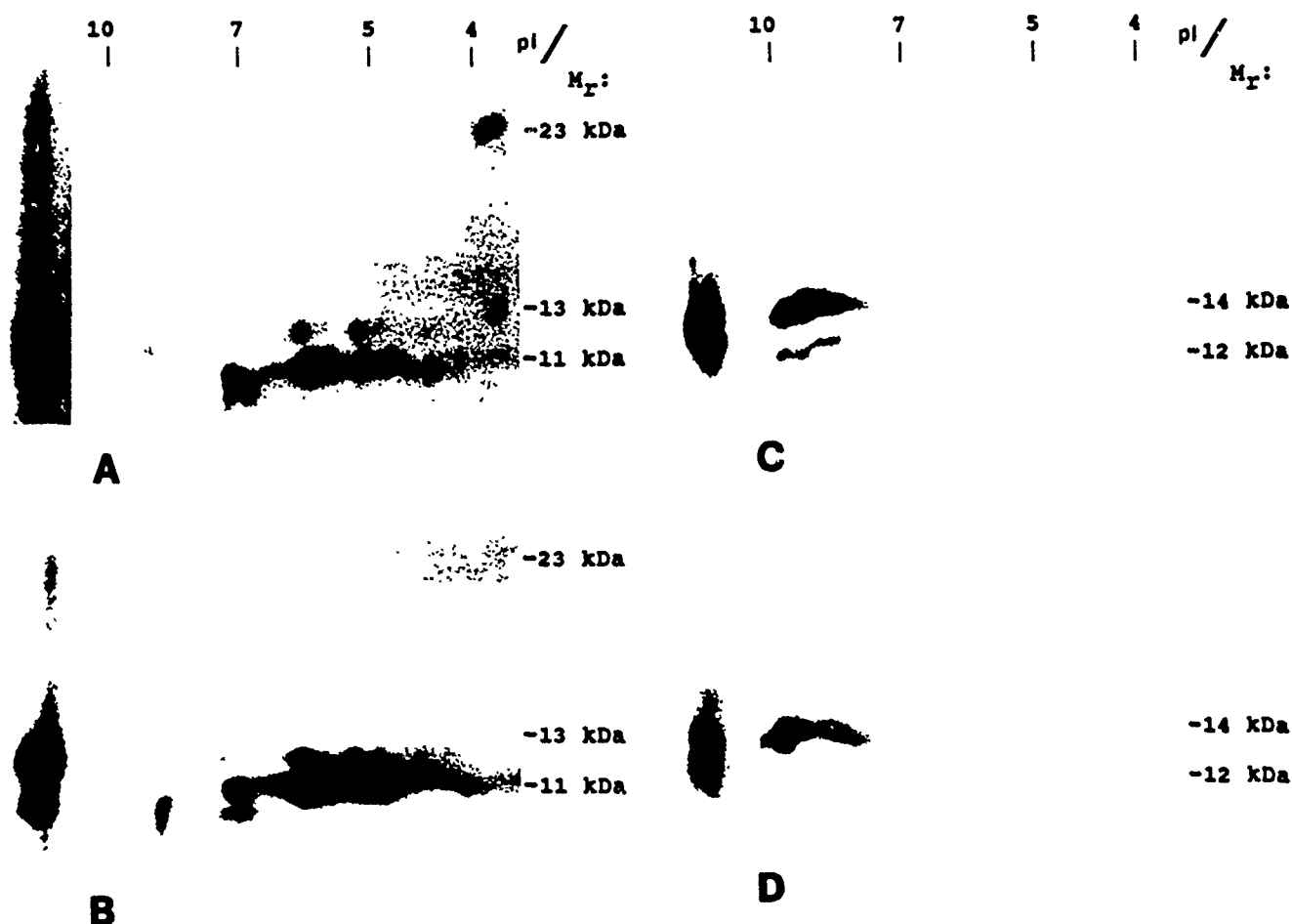


Figure 4. Phosphopeptide maps of GCP and P_2 proteins following limited proteolysis by *S. aureus* V8 protease. Endogenously labeled proteins were harvested from 2-dimensional gels and were prepared for analysis on 1- or 2-dimensional gels as described in Materials and Methods. In each case, a 1-dimensional separation of phosphopeptides is shown in a lane at left, and a 2-dimensional NEPHGE-SDS separation of the same phosphopeptides is shown at right: *A*, protein F1 from P_2 ; *B*, pp46 from GCPs; *C*, 80k from P_2 ; *D*, pp80 from GCPs. Autoradiographs are representative of several comparisons.

ylation of pp46, pp80, protein F1, and 80k in the presence of PKC-stimulating phorbol esters has also been found (Hyman and Pfenninger, 1987; R. B. Nelson, D. J. Linden, and A. Routtenberg, unpublished observations).

With regard to other kinase systems, a moderate stimulation of pp46 phosphorylation (~20%) in the presence of exogenous calmodulin (CaM) and high Ca^{2+} has been reported (Katz et al., 1985). In contrast to PKC, however, 3 Ca^{2+} /CaM-stimulated kinases tested to date have failed to phosphorylate purified protein F1 (Chan et al., 1986). It is possible, then, that the CaM effect on F1/pp46 phosphorylation does not occur directly through a Ca^{2+} /CaM-stimulated kinase. Addition of cAMP does not increase phosphorylation of pp46 or protein F1 (Conway and Routtenberg, 1978; Ellis et al., 1985), nor is purified protein F1 phosphorylated by exogenous cAMP-dependent kinase (Chan et al., 1986).

Phosphorylation of protein F1, pp46, 80k, and pp80 could all be stimulated in a dose-dependent manner by exogenous purified PKC (Table 1), however, this increase was dose dependent for the adult brain proteins only after a pH extract of P_2 proteins was precipitated between 40 and 80% saturation with ammonium sulfate. This treatment removes a PKC inhibitory factor (Chan et al., 1985). Such PKC inhibitory factors have

been described previously (Albert et al., 1984; Schwantke and LePeuch, 1984; McDonald and Walsh, 1985). Interestingly, the growth cone preparation required no such treatment for PKC stimulation to be dose dependent, suggesting that the PKC inhibitory factor is absent or present in much lower concentrations in the growth cone preparation and may thus be developmentally regulated. The lack of this inhibitory factor may also account in part for the high endogenous levels of PKC substrate phosphorylation found in the growth cone preparation. Recently, purified protein F1 has been shown to be a high-affinity substrate for purified PKC (Chan et al., 1986), as has a purified protein believed to be the same as 80k and pp80 (Wu et al., 1982; Blackshear et al., 1986). These findings strengthen the notion that F1/pp46 and 80k/pp80 are physiological substrates for PKC.

Protein F1 and pp46 were both stimulated by addition of PS in the presence of low Ca^{2+} and TX-100, but the percentage stimulation was higher for protein F1 (Fig. 5). This may have been due to the already high basal kinase activity found in growth cones, i.e., PS-stimulated kinase activity may be near maximal activation. A related possibility is that pp46 might be close to saturation with unlabeled phosphate groups, leading to a lack of available unphosphorylated substrate during the *in*

vitro assay. pp80 phosphorylation and 80k were only moderately stimulated by addition of PS in the current study (Fig. 5B). Although both of these proteins have been strongly stimulated by addition of PS in previous studies (Wu et al., 1982; Katz et al., 1985; R. B. Nelson and A. Routtenberg, unpublished observations), those studies measured 80k and pp80 phosphorylation in soluble fractions with no membrane present, in contrast to the present study. Since PS itself is a membrane component, it is likely that the presence of other membrane elements in the phosphorylation assay make PS of limited use in showing quantitative stimulation of PKC in membrane-containing samples.

Using quantitative analysis of 2-dimensional gels, we found in the present study that the *in vitro* phosphorylation of 80k in adult dorsal hippocampus was directly correlated to the persistence over 10 min of LTP induced *in vivo* (Fig. 6). This experiment also replicated a direct correlation of protein F1 with the persistence of LTP. When the same experimental samples were separated by 1-dimensional SDS-PAGE alone, only the correlation of protein F1 to persistence of LTP was detectable, indicating that the effect on 80k is masked by its comigration with the major phosphoprotein doublet found in adult brain, synapsin Ia and Ib.

These results indicate, first, that protein F1 is not unique among PKC substrates in being correlated with persistence of LTP and, instead, suggest that the neural PKC system is important for relating PKC activity to adult synaptic plasticity. Because recent reports indicate that changes in PKC activity are a cause, rather than a consequence, of changes in persistence in LTP (Routtenberg et al., 1986; Linden et al., 1987; Lovinger et al., 1987), determining the functional roles of these different neural PKC substrates is now a key question in understanding the biochemical mechanisms underlying LTP.

The phosphorylation of protein F1/pp46 and 80k/pp80 paralleled each other in the present study both with regard to their relationship to persistence of LTP and their enrichment in GCPs. Previously, both proteins were also shown to exhibit gradients of 32 P incorporation along the occipitotemporal visual processing pathway in rhesus monkey cerebral cortex (Nelson et al., 1987). These gradients peak in medial temporal areas important for storage of visual recognition memory.

There are also contrasts in the characteristics of protein F1/pp46 versus 80k/pp80, in which 80k/pp80 behaves as both an integral membrane protein and a soluble protein during subcellular fractionation (Albert et al., 1986), whereas protein F1/pp46 has only been found in membrane-associated fractions (Zwiers et al., 1980; Skene and Willard, 1981c; Katz et al., 1985; Nelson and Routtenberg, 1985; Simkowitz et al., 1989). Moreover, protein F1/pp46, as the B-50 protein (Gispen et al., 1986), is thought to be brain-specific and presynaptically localized (Kristjansson et al., 1982; Gispen et al., 1985), while 80k/pp80 appears to have a widespread distribution among tissues and species (Albert et al., 1986), similar to that of PKC (Kuo et al., 1980). Protein F1/pp46 has recently been identified with GAP43* (Skene and Willard, 1981a-c; Benowitz and Lewis, 1983; Meiri et al., 1986; Snipes et al., 1987), a protein whose synthesis is greatly increased following nerve crush or axotomy. No such changes in synthesis during regeneration have been reported for 80k/pp80. Finally, 80k/pp80 was recently reported to be covalently bound to myristic acid (Perrone-Bizzozero et

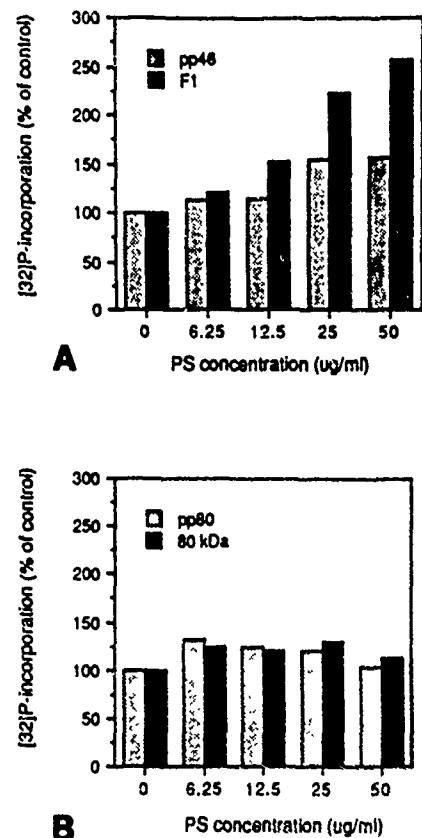


Figure 5. Effects of exogenous PS on 32 P incorporation into (A) protein F1 and pp46 and (B) 80 kDa and pp80. Aliquots from a common source (P₂ or GCPs) were incubated on ice in the presence of 0.15% TX-100 for 10 min. Duplicate samples were incubated with increasing concentrations of PS as indicated. Final reaction conditions were the same as in Figure 1 except that samples contained a final concentration of 0.075% TX-100. Labeled proteins were excised from 2-dimensional gels using the autoradiograph as a guide and counted for radioactive phosphate as described in Materials and Methods. Comparison shows the percentage of stimulation from control levels. Each value is an average of 2 determinations.

al., 1987), whereas protein F1/pp46 does not appear to have this posttranslational modification.

F1/pp46 and 80k/pp80 were moderately labeled proteins among 20 or more major phosphoproteins detected in adult hippocampus, but were the 2 highest endogenously labeled phosphoproteins detected in the growth cone-enriched preparation (Fig. 1). It is intriguing to ask what role these major growth cone phosphoproteins might have in the neuropil of mature CNS. Since the phosphorylation of both of these proteins is related to persistence of LTP (Fig. 6), one hypothesis is that adult neural plasticity as modeled by LTP may involve molecular mechanisms employed during nervous system development, i.e., neurite growth. If such were the case, the appearance of LTP might require either restructuring of adult synapses or possibly terminal sprouting and the formation of new synapses (Routtenberg, 1985, 1986; Pfenninger, 1986; Pfenninger et al., 1986). Changes in synapse morphology of hippocampal neurons following induction of LTP has been observed (Lee et al., 1980; Desmond and Levy, 1983; Greenough, 1984). Such a model of neural plasticity was proposed as a basis for information storage several decades ago (Hebb, 1949).

The present findings make it attractive to propose that a com-

* Both GAP43 and B-50 have been reported to be present in purified growth cone preparations (De Graan et al., 1985; Meiri et al., 1986; Skene et al., 1986).

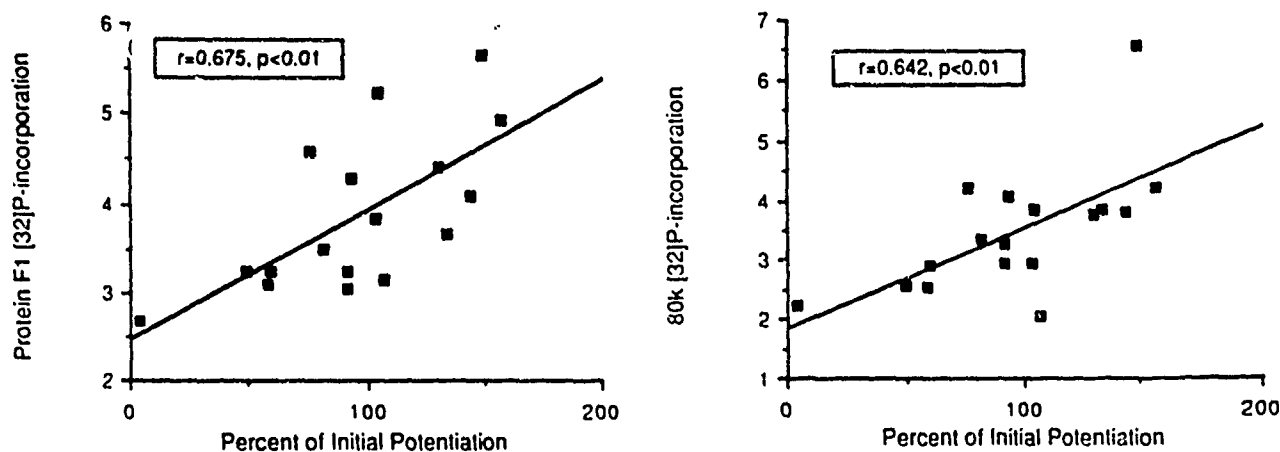


Figure 6. Scatterplots comparing *in vitro* phosphorylation of protein F1/pp46 and 80k/pp80 in adult rat dorsal hippocampal formation with persistence of initial potentiation remaining in the population spike amplitude after 10 min. The units on the abscissa are $\text{cpm} \times 10^3$, while the percentage on the ordinate is a measure of persistence of spike amplitude: e.g., 100% would mean the increase in spike amplitude following high-frequency stimulation did not change from 3 to 13 min, 200% would mean the increase in spike amplitude doubled over that time, and 0% would mean the increase in spike amplitude decayed back to the prestimulation baseline during that time. Each point is derived from an individual test animal. ^{32}P -labeled proteins from each of 17 LTP test animals were separated by NEPHGE-SDS, excised from the gels, and then counted by liquid scintillation (see Materials and Methods). The reaction with $\gamma\text{-}^{32}\text{P}$ -ATP is described in Materials and Methods. The final reaction volume was 40 μl containing 1 mg/ml protein, 5 μM $\gamma\text{-}^{32}\text{P}$ -ATP (100 μCi), 30 mM potassium phosphate (pH 7.1), 2 mM Mg^{2+} , 1 mM EDTA, and 1 mM DTT.

mon molecular mechanism—involving F1/pp46, 80k/pp80, and PKC—may underlie both normal neurite growth in developing brain and neural plasticity of adult synapses.

References

- Akers, R. F., and A. Routtenberg (1985) Kinase C phosphorylates a protein involved in synaptic plasticity. *Brain Res.* 334: 147–151.
- Akers, R. F., D. Lovinger, P. Colley, D. Linden, and A. Routtenberg (1986) Translocation of protein kinase C activity may mediate hippocampal long term potentiation. *Science* 231: 587–589.
- Albert, K. A., W. C. S. Wu, A. C. Nairn, and P. Greengard (1984) Inhibition by calmodulin of calcium/phospholipid-dependent protein phosphorylation. *Proc. Natl. Acad. Sci. USA* 81: 3622–3625.
- Albert, K. A., S. I. Walaas, J. K. T. Wang, and P. Greengard (1986) Widespread occurrence of “87 kDa,” a major specific substrate for protein kinase C. *Proc. Natl. Acad. Sci. USA* 83: 2822–2826.
- Benowitz, L. I., and E. R. Lewis (1983) Increased transport of 44,000- to 49,000-dalton acidic proteins during regeneration of the goldfish optic nerve: A two-dimensional gel analysis. *J. Neurosci.* 3: 2153–2163.
- Blackshear, P. J., L. Wen, B. P. Glynn, and L. A. Witters (1986) Protein kinase C-stimulated phosphorylation in response to phorbol esters and growth factors in intact fibroblasts. *J. Biol. Chem.* 261: 1459–1469.
- Bliss, T. V. P., and T. Lomo (1973) Long lasting potentiation of synaptic transmission in the dentate area of the anesthetized rabbit following stimulation of the perforant path. *J. Physiol. (Lond.)* 232: 357–374.
- Burgess, S. K., N. Sahyoun, S. G. Blanchard, H. LeVine III, K. J. Chang, and P. Cuatrecasas (1986) Phorbol ester receptors and protein kinase C in primary neuronal cultures: Development and stimulation of endogenous phosphorylation. *J. Cell Biol.* 102: 312–319.
- Castagna, M., Y. Takai, K. Kaibuchi, K. Sano, U. Kikkawa, and Y. Nishizuka (1982) Direct activation of calcium-activated, phospholipid-dependent protein kinase by tumor-promoting phorbol esters. *J. Biol. Chem.* 257: 7847–7851.
- Chan, S. Y., K. Murakami, and A. Routtenberg (1985) Purification of a kinase C substrate: Brain phosphoprotein F1 and an endogenous kinase C inhibitory factor. *Soc. Neurosci. Abstr.* 11: 926.
- Chan, S. Y., K. Murakami, and A. Routtenberg (1986) Phosphoprotein F1: Purification and characterization of a brain kinase C substrate related to plasticity. *J. Neurosci.* 6: 3618–3627.
- Cleveland, D. W., S. G. Fischer, M. W. Kirschner, and U. K. Laemmli (1977) Peptide mapping by limited proteolysis in sodium dodecyl sulfate and analysis by gel electrophoresis. *J. Biol. Chem.* 252: 1102–1106.
- Conway, R. G., and A. Routtenberg (1978) Endogenous phosphorylation *in vitro*: Selective effects of sacrifice methods on electrophoretically separated protein bands. *Brain Res.* 139: 366–373.
- De Graan, P. N. E., C. O. M. Van Hooff, B. C. Tilly, A. B. Oestricher, P. Schotman, and W. H. Gispen (1985) Phosphoprotein B-50 in nerve growth cones from fetal rat brain. *Neurosci. Lett.* 8: 235–241.
- Desmond, N. L., and W. B. Levy (1983) Synaptic correlates of associative potentiation/depression: An ultrastructural study in the hippocampus. *Brain Res.* 265: 21–30.
- Ellis, L., F. Katz, and K. H. Pfenninger (1985) Nerve growth cones isolated from fetal rat brain: II. Cyclic adenosine 3':5'-monophosphate (cAMP)-binding proteins and cAMP-dependent protein phosphorylation. *J. Neurosci.* 5: 1393–1401.
- Gispen, W. H., J. L. M. Leunissen, A. B. Oestricher, A. J. Verkleij, and H. Zwiers (1985) Presynaptic localization of B-50 phosphoprotein: The (ACTH)-sensitive protein kinase substrate involved in rat brain polyphosphoinositide metabolism. *Brain Res.* 328: 381–385.
- Gispen, W. H., P. N. E. De Graan, S. Y. Chan, and A. Routtenberg (1986) Comparison between the neural acidic proteins B50 and F1. *Prog. Brain Res.* 69: 383–386.
- Greenough, W. T. (1984) Structural correlates of information storage in the mammalian brain: A review and hypothesis. *Trends Biochem. Sci.* 7: 229–233.
- Hebb, D. O. (1949) *The Organization of Behavior*, p. 335, Wiley, New York.
- Hsu, L., D. Natzyk, and J. D. Laskin (1984) Effects of the tumor promoter 12-O-tetradecanoylphorbol-13-acetate on neurite outgrowth from chick embryonic sensory ganglia. *Cancer Res.* 44: 4607–4614.
- Hyman, C., and K. H. Pfenninger (1987) Intracellular regulators of neuronal sprouting: II. Phosphorylation reactions in isolated growth cones. *J. Neurosci.* 7: 4076–4083.
- Katz, F., L. Ellis, and K. H. Pfenninger (1985) Nerve growth cones isolated from fetal rat brain: Calcium-dependent protein phosphorylation. *J. Neurosci.* 5: 1402–1411.
- Kikkawa, U., Y. Takai, R. Minakuchi, S. Inohara, and Y. Nishizuka (1982) Calcium-activated, phospholipid-dependent protein kinase from rat brain. *J. Biol. Chem.* 257: 13341–13348.
- Kraft, A. S., and W. B. Andersen (1983) Phorbol esters increase the amount of calcium, phospholipid-dependent protein kinase associated with the plasma membrane. *Nature* 301: 621–623.

- Kristjansson, G. I., H. Zwiers, A. B. Oestricher, and W. H. Gispen (1982) Evidence that the synaptic phosphoprotein B50 is localized exclusively in nerve tissue. *J. Neurochem.* 39: 371-378.
- Kuo, J. F., R. G. G. Andersson, B. B. Wise, L. Mackerlova, I. Salomonsson, N. L. Brackett, N. Katoh, and R. W. Wrenn (1980) Calcium-dependent protein kinase: Widespread occurrence in various tissues and phyla of the animal kingdom and comparison of effects of phospholipid, calmodulin, and trifluoperazine. *Proc. Natl. Acad. Sci. USA* 77: 7039-7043.
- Laemmli, U. K. (1970) Cleavage of structural proteins during the assembly of bacteriophage T4. *Nature* 227: 680-685.
- Lee, K. S., F. Schottler, M. Oliver, and G. Lynch (1980) Brief bursts of high-frequency stimulation produce two types of structural change in rat hippocampus. *J. Neurophysiol.* 44: 247-258.
- Linden, D. J., F. S. Sheu, K. Murakami, and A. Routtenberg (1987) Enhancement of long-term potentiation by cis-unsaturated fatty acid: Relationship to protein kinase C and phospholipase A₂. *J. Neurosci.* 7: 3783-3792.
- Lovinger, D. M., R. F. Akers, R. B. Nelson, C. A. Barnes, B. L. McNaughton, and A. Routtenberg (1985) A selective increase in the phosphorylation of protein F1, a protein kinase C substrate, directly related to three day growth of long-term synaptic enhancement. *Brain Res.* 343: 137-143.
- Lovinger, D. M., P. A. Colley, R. F. Akers, R. B. Nelson, and A. Routtenberg (1986) Direct relation of long-duration synaptic potentiation to phosphorylation of membrane protein F1: A substrate for membrane protein kinase C. *Brain Res.* 339: 205-211.
- Lovinger, D. M., K. L. Wong, K. Murakami, and A. Routtenberg (1987) Protein kinase C inhibitors eliminate hippocampal long-term potentiation. *Brain Res.* 436: 177-183.
- Lowry, O. N., J. Rosebrough, and R. J. Randall (1951) Protein measurement with the Folin phenol reagent. *J. Biol. Chem.* 193: 265-275.
- Matus, A. I., M. L. Ng, and J. P. Mazat (1980) Protein phosphorylation in synaptic membranes: Problems of interpretation. In *Protein Phosphorylation and Bio-Regulation*, G. Thomas, E. J. Podesta, and J. Gorson, eds., pp. 25-36, Karger, Basel.
- McDonald, J. R., and M. P. Walsh (1985) Ca²⁺-binding protein from bovine brain including a potent inhibitor of protein kinase C. *Biochem. J.* 232: 559-567.
- Meiri, K. F., K. H. Pfenninger, and M. B. Willard (1986) Growth-associated protein, GAP-43, a polypeptide that is induced when neurons extend axons, is a component of growth cones and corresponds to pp46, a major polypeptide of a subcellular fraction enriched in growth cones. *Proc. Natl. Acad. Sci. USA* 83: 3537-3541.
- Merril, C. R., D. Goldman, S. A. Sedman, and M. H. Ebert (1981) Ultrasensitive stain for proteins in polyacrylamide gels shows regional variation in cerebrospinal fluid proteins. *Science* 211: 1437-1438.
- Mitrus, J. C., D. G. Morgan, and A. Routtenberg (1981) *In vivo* phosphorylation following ³²P-orthophosphate injection into neostriatum or hippocampus: Selective and rapid labelling of electrophoretically-separated proteins. *Brain Res.* 212: 67-81.
- Murakami, K., and A. Routtenberg (1985) Direct activation of purified protein kinase C by unsaturated fatty acids (oleate and arachidonate) in the absence of phospholipids and Ca²⁺. *FEBS Lett.* 192: 189-193.
- Murphy, K. M. M., R. J. Gould, M. L. Oster-Granite, J. D. Gearheart, and S. H. Snyder (1983) Phorbol ester receptors: Autoradiographic identification in the developing rat. *Science* 222: 1036-1038.
- Nagle, D. S., S. Jake, M. Castagna, and P. M. Blumberg (1981) Variation with embryonic development and regional localization of specific [³H]phorbol 12,13-dibutyrate binding to brain. *Cancer Res.* 41: 89-93.
- Natyzak, L. H. D., and J. D. Laskin (1984) Effects of the tumor promoter 12-o-tetradecanoylphorbol-13-acetate on neurite outgrowth from chick embryo sensory ganglia. *Cancer Res.* 44: 4607-4614.
- Nelson, R. B., and A. Routtenberg (1985) Characterization of the 47kD protein F1 (pI 4.5), a kinase C substrate directly related to neural plasticity. *Exp. Neurol.* 89: 213-224.
- Nelson, R. B., D. P. Friedman, J. B. O'Neill, M. Mishkin, and A. Routtenberg (1987) Gradients of protein kinase C substrate phosphorylation in primate visual system peak in visual memory storage areas. *Brain Res.* 416: 387-392.
- Nestler, E. J., and P. Greengard (1986) Synapsin I: A review of its distribution and biological regulation. *Brain Res.* 69: 323-340.
- Niedel, J. E., L. J. Kuhn, and G. R. Vandenberg (1983) Phorbol diester receptor copurifies with protein kinase C. *Proc. Natl. Acad. Sci. USA* 80: 36-40.
- O'Farrell, P. H. (1975) High resolution two-dimensional electrophoresis of proteins. *J. Biol. Chem.* 250: 4007-4021.
- O'Farrell, P. Z., H. M. Goodman, and P. H. O'Farrell (1977) High resolution two-dimensional electrophoresis of basic as well as acidic proteins. *Cell* 12: 1133-1142.
- Perrone-Bizzozero, N. I., P. J. Apostolides, S. P. Finklestein, L. I. Benowitz, and O. Bizzozero (1987) *Soc. Neurosci. Abstr.* 17: 1478.
- Pfenninger, K. H. (1986) Of nerve growth cones, leukocytes and memory: Second messenger systems and growth-regulated proteins. *Trends Neurosci.* 9: 562-565.
- Pfenninger, K. H., L. Ellis, M. P. Johnson, L. B. Friedman, and S. Somlo (1983) Nerve growth cones isolated from fetal rat brain. I. Subcellular fractionation and characterization. *Cell* 35: 573-584.
- Pfenninger, K. H., C. Hyman, and R. S. Garofalo (1986) Protein phosphorylation in the nerve growth cone. *Prog. Brain Res.* 69: 235-244.
- Rosenthal, A., S. Y. Chan, W. Henzel, C. Haskell, W. J. Kuang, E. Chen, J. N. Wilcox, A. Ullrich, D. V. Goeddel, and A. Routtenberg (1987) Primary structure and mRNA localization of protein F1, a growth-related protein kinase C substrate associated with synaptic plasticity. *EMBO J.* 6: 3641-3646.
- Routtenberg, A. (1985) Protein kinase C activation leading to protein F1 phosphorylation may regulate synaptic plasticity by presynaptic terminal growth. *Behav. Neural Biol.* 44: 186-200.
- Routtenberg, A. (1986) Synaptic plasticity and protein kinase C. *Prog. Brain Res.* 69: 211-234.
- Routtenberg, A., D. M. Lovinger, and O. Steward (1985) Selective increase in the phosphorylation of a 47kD protein (F1) directly related to long-term potentiation. *Behav. Neural Biol.* 43: 3-11.
- Routtenberg, A., P. Colley, D. Linden, D. Lovinger, K. Murakami, and F. S. Sheu (1986) Phorbol ester promotes growth of synaptic plasticity. *Brain Res.* 378: 374-378.
- Sbaschnig-Agler, M., K. H. Pfenninger, and R. W. Ledeen (1988) Gangliosides and other lipids of the growth cone membrane. *J. Neurochem.* 51: 212-220.
- Schwantke, N., and C. J. Le Peuch (1984) A protein kinase C inhibitory activity is present in rat brain homogenate. *FEBS Lett.* 177: 36-40.
- Simkowitz, P., L. Ellis, and K. H. Pfenninger (1989) Membrane proteins of the nerve growth cone and their developmental regulation. *J. Neurosci.* (in press).
- Skene, J. H. P., and M. Willard (1981a) Changes in axonally transported proteins during axon regeneration in toad retinal ganglion cells. *J. Cell Biol.* 89: 86-95.
- Skene, J. H. P., and M. Willard (1981b) Axonally transported proteins associated with axon growth in rabbit central and peripheral nervous system. *J. Cell Biol.* 89: 96-103.
- Skene, J. H. P., and M. Willard (1981c) Characteristics of growth-associated polypeptides in regenerating toad retinal ganglion cell axons. *J. Neurosci.* 1: 419-426.
- Skene, J. H. P., R. D. Jacobson, G. J. Snipes, C. B. McGuire, J. J. Norden, and J. A. Freeman (1986) A protein induced during nerve growth (GAP-43) is a major component of growth cone membranes. *Science* 233: 783-785.
- Snipes, J., S. Chan, C. B. McGuire, B. R. Costello, J. J. Norden, J. A. Freeman, and A. Routtenberg (1987) Evidence for the co-identification of GAP-43, a growth-associated protein, and F1, a plasticity-associated protein. *J. Neurosci.* 7: 4066-4075.
- Ueda, T., and P. Greengard (1977) Adenosine 3':5' monophosphate-regulated phosphoprotein system of neuronal membranes. I. Solubilization, purification, and some properties of an endogenous phosphoprotein. *J. Biol. Chem.* 252: 5155-5163.
- Wu, W. C., S. I. Walaas, A. C. Nairn, and P. Greengard (1982) Calcium/phospholipid regulates phosphorylation of a Mr "87k" substrate protein in brain synaptosomes. *Proc. Natl. Acad. Sci. USA* 79: 5249-5253.
- Zwiers, H., P. Schotman, and W. H. Gispen (1980) Purification and some characteristics of an ACTH-sensitive protein kinase and its substrate protein in rat brain membranes. *J. Neurochem.* 33: 247-256.

CONCURRENCE FORM

The Armstrong Aerospace Medical Research Laboratory requests the continuation of the AFOSR fellowship for Mr. John F. Larish, studying Engineering Psychology at University of Illinois at Urbana-Champaign.

Give a brief statement of laboratory and/or Dr. Rick Warren's (fellow's mentor) involvement with Mr. John F. Larish.

FREQUENT PHONE CONTACT IS MAINTAINED.
DR. WARREN MET WITH JOHN LARISH AT THE
AVIATION PSYCHOLOGY SYMPOSIUM IN COLUMBUS, (C)
IN MAY 1989. THE STUDENT'S ACADEMIC PROGRESS
AND RESEARCH ACTIVITIES WERE DISCUSSED.
PLANS ARE BEING MADE BY DR. WARREN
TO HAVE JOHN LARISH ATTEND THE FALL
REVIEW OF AFOSR SPONSORED COGNITIVE
PSYCHOLOGY RESEARCH PROJECTS. AFOSR PERMITTED
LAST YEAR SINCE IT IS ENTIRELY APPROPRIATE
TO HAVE AN AFOSR FELLOW IN COGNITION ATTEND
THE AFOSR COGNITIVE REVIEW.

George Uchida 16 JUL 89

Chief Scientist Date

Dr. Rick Warren 3 JUL 89

Mentor Date

DR RICHARD WARREN
AAMRL/HEF
WPAFB OH 45433-6573

Certification Needed for Each Academic Term
CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. John Larish

Semester/Academic Term: Spring 1989

University: University of Illinois

Subcontract: S-789-000-004

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet extra space is needed.)

Psychology 415: Experimental Sensory Psychology. Instructor: Dr. G. J. Andersen. This class studied visual processes in humans at a low psychophysical level. Topics included mechanisms of spatial and temporal vision, brightness perception, and color perception. Grade Received: A

Psychology 493AA: Psychological Research on International Security. Instructor: Dr. S. Plous. This seminar examined a wide range of topics in both psychology and political science relating to international security and conflict resolution. An emphasis was placed on the application of research to actual world problems at both a national and international policy level. Grade Received: A. (Continued on separate sheet.)

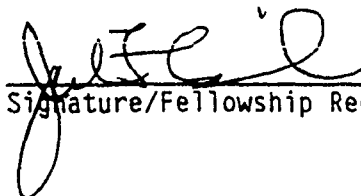
2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

See attached sheet.

3. Give brief statement of your involvement with the Armstrong Aerospace Medical Research Laboratory and Dr. Rik Warren. Also list any items of interest such as academic awards, publications, other information that can be used for LGFP newsletter.

See attached sheet.

"I certify that all information stated is correct and complete."


Signature/Fellowship Recipient

John F. Larish
TYPED NAME/FELLOWSHIP RECIPIENT

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. John Larish is making satisfactory academic progress toward a Ph.D. in the area of Engineering Psychology for the Spring 1989 academic term."


Signature/Advising Professor

Dr. John M. Flach, Assistant Professor
TYPED NAME/TITLE OF ADVISING
PROFESSOR

2094t

Question 1 (continued).

Psychology 499: Thesis credit. An in-depth survey of visual issues in spatial disorientation was conducted with particular emphasis on aviation. A series of research questions has been developed from this review from which my dissertation proposal will be drawn.

Grade Received: Satisfactory.

Question 2.

I spent a large amount of time during the Spring semester examining visual issues in spatial disorientation. I have outlined several research questions to examine in my dissertation. These include the effects of visual field size, scene quality, presence versus absence of aircraft framing cues, and the use of HUDs in spatial disorientation in a pursuit flying task. Differences in perceived orientation for active versus passive observers will also be examined. The variables to be studied have importance both in addressing theoretical issues in the study of human orientation as well as having direct application to aviation and flight simulation. Dr. G. J. Andersen will advise me for this study. My dissertation proposal will be prepared during the Summer session.

The study of error responses by pilots, drivers, and computer operators was completed. This study demonstrated that interesting, and somewhat counterintuitive consistencies exist in the pattern of errors made by users of different complex systems. The study was presented by Dr. Flach as a paper at the Fifth Symposium on Aviation Psychology, where it was well received.

A third area of research involved the continued development of the study of altitude control over changing ground surface elevation begun last summer at AAMRL, WPAFB. Changes in program design have led to improvements in frame rate and data collection accuracy, allowing for finer-grained frequency analysis.

A final area of research was in assisting John Flach and Brent Hagen in the completion of a study of visual sources of optical information for altitude control. This study is currently being prepared for submission for publication.

Question 3.

Dr. Warren and I maintain periodic contact by phone to keep abreast of developments in one another's research. I also had the opportunity to talk with Dr. Warren and several of his colleagues from AAMRL at the Symposium of Aviation Psychology in May. The possibility of future cooperative work with Dr. Warren to be conducted at Illinois has also been discussed.

The paper "Sources of optical information useful for the perception of rectilinear self-motion" written by myself and Dr. John Flach has been

accepted for publication by the Journal of Experimental Psychology: Human Perception and Performance. The paper is expected to appear in the journal around May 1990. This paper is an abbreviated version of my masters thesis.

CONCURRENCE FORM

The Armstrong Aerospace Medical Research Laboratory requests the continuation of the AFOSR fellowship for Mr. John F. Larish, studying Engineering Psychology at University of Illinois at Urbana-Champaign.

Give a brief statement of laboratory and/or Mr. Rick Warren's (fellow's mentor) involvement with Mr. John F. Larish.

The Mentor - Dr. RIK WARREN - HAS FREQUENT PHONE CONTACT WITH THE STUDENT ABOUT RESEARCH OF COMMON INTEREST. IT IS THE MENTOR'S BELIEF THAT AN AIR FORCE FELLOW SHOULD LEARN SOMETHING ABOUT AIR FORCE RESEARCH. THEREFORE, ARRANGEMENT WERE MADE FOR MR. LARISH TO ATTEND A REVIEW OF AFOSR SPONSORED COGNITIVE RESEARCH. THE REVIEW WAS HELD AT THE AF ACADEMY. JOHN LARISH CONTINUES TO BE AN EXEMPLARY AFF

 19 May 89

Chief Scientist

Date

 8 MAY 89

Mentor

Date

RICHARD WARREN
AAMRL/HEF
WPAFB OH 45433-6573

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. John Larish

Semester: Fall 1988

University: University of Illinois

Subcontract: S-789-000-004

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

ME 497B: Human Error in Complex Systems. Instructor: Dr. N. Moray. This course examined the study of human error and models of error involving human operators in complex systems. (Note : Last required course.)

Grade received: A

PSYCH 499: Thesis credit. Most work this semester went towards studying for the qualifying exams and preliminary development of dissertation topic.

Grade received: Satisfactory

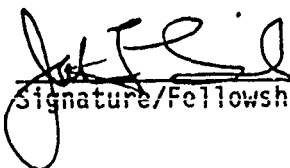
2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

see attached sheet

3. Give brief statement of your involvement with the Armstrong Aerospace Medical Research Laboratory Laboratory and Dr. Rik Warren.

see attached sheet

"I certify that all information stated is correct and complete."


Signature/Fellowship Recipient

John F. Larish

TYPED NAME/FELLOWSHIP RECIPIENT

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. John Larish is making satisfactory academic progress toward a Ph.D. in the area of Engineering Psychology in the discipline of Engineerin Psychology for the Fall 1988 semester."


Signature/Advising Professor

Dr. John M. Flach, Assistant Professor

TYPED NAME/TITLE OF ADVISING
PROFESSOR

2094t

Question 2.

Progress towards graduation took place in three areas during the Fall 1989 semester. I successfully passed the qualifying examination. This involved completing a two part written examination prepared by a committee of four faculty members and is tailored to the interests of individual students. The which I read for were visual perception, manual control, human performance models, and multi-operator interaction, specifically in the context of the cockpit.

I also began to research potential dissertation topics with the goal of preparing and defending my proposal by the end of the Summer. My dissertation will probably involve visual issues in spatial disorientation.

The mechanical engineering course listed in Question 1 was the final required course and completed my minor. From this point, any classes will simply be things I am interested in taking or think I should learn about.

Three different research projects were in progress during the Fall semester. First, my masters research is currently submitted for publication to the Journal of Experimental Psychology: Human Perception and Performance. It has undergone several revisions and a final decision is expected from the editor in the late Spring.

The survey of pilot error that was in begun in 1987 in association with John Flach and Lisa Weinstein has been analyzed and has been accepted for presentation at the Fifth Symposium on Aviation Psychology. Data collection, both for errors involving aircraft as well as other technical systems (computers, automobiles) will continue in the Spring.

Programming was also developed during the fall for an experiment to study control of altitude over changing ground surface texture and elevation. This study is an extension of work begun at AAMRL, WPAFB during the 1988 Summer GSRP program. Subject running is expected to begin in the Spring of 1989.

Question 3.

During the Fall semester I was frequently in contact with Dr. Warren. We spoke on the phone periodically so we could compare notes on our respective research projects and to exchange ideas. This has proved extremely helpful to me in developing new directions for research.

In September, I accompanied Dr. Warren to the AFOSR Cognitive Review, held at the Air Force Academy. This allowed me the opportunity to meet many highly respected psychologists who are currently conducting research for the Air Force in a relatively informal setting and to hear about their work. This was an excellent opportunity, and it was very generous of Dr. Warren to arrange permission for me to attend. The meeting also allowed us to meet in person and to discuss ideas in more detail than is possible by telephone. I have found such periodic meeting with Dr. Warren to be very beneficial to me and are something that should be encouraged for all graduate fellows and their mentors.

CONCURRENCE FORM

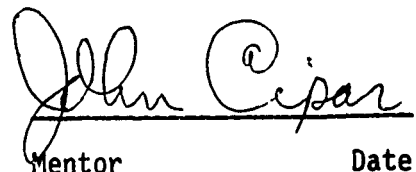
The Geophysics Laboratory requests the continuation of the AFOSR fellowship for Ms. Lind S. Gee, studying Earth Sciences at Massachusetts Institute of Technology.

Give a brief statement of laboratory and/or Dr. John Cipar's (fellow's mentor) involvement with Ms. Lind S. Gee.

Lind Gee is the co-author of an AFGL report entitled "Investigations of Eurasian Seismic Sources and Upper Mantle Structure". She has made considerable progress toward her Ph.D. degree in this semester.



Chief Scientist Date
21 JUN 89



Mentor Date
6/20/89

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Ms. Lind Gee

Semester: Spring 1989

University: Massachusetts Institute of Tech.

Subcontract: S-789-000-005

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

<u>Courses</u>	<u>Units</u>	<u>Grades</u>
Spring '89 Thesis	48	Satisfactory progress

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

I am in the final stages of preparing my thesis. I anticipate defending by the end of the summer. Enclosed is a draft of a paper to be submitted to Geophysical Journal before the end of the summer.

3. Give brief statement of your involvement with the Geophysics Laboratory Laboratory and Dr. John Sipar.

I have discussed my thesis research with Dr. Cipar several times in the past year. I hope to schedule a seminar at the Geophysics Lab in the early fall.

"I certify that all information stated is correct and complete."



Signature/Fellowship Recipient

Lind S. Gee
TYPED NAME/FELLOWSHIP RECIPIENT

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Ms. Lind Gee is making satisfactory academic progress toward a Ph.D. in the area of Earth Sciences for the Spring 1989 academic term."



Signature/Advising Professor

Thomas H. Jordan, Professor of Geophysics

TYPED NAME/TITLE OF ADVISING
PROFESSOR

2094t

CONCURRENCE FORM

The Geophysics Laboratory requests the continuation of the AFOSR fellowship for Ms. Lind S. Gee, studying Earth Sciences at Massachusetts Institute of Technology.

Give a brief statement of laboratory and/or Dr. John Cipar's (fellow's mentor) involvement with Ms. Lind S. Gee.

I visited Lind Gee in January 1989 at MIT. We discussed her work on seismic anisotropy of the Eurasian Upper Mantle. Our laboratory is planning a research program to further define the structure of the mantle discontinuities using newly available Chinese and Soviet data. Her progress toward her degree is excellent, and she should make several important contributions in the papers ~~and~~ she is currently writing.

for *A. J. Jurena*
Chief Scientist Date *1 May 89*

John Cipar *27 Apr 89*
Mentor Date

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Ms. Lind Gee

Semester: Fall 1988

University: Massachusetts Institute of Tech.

Subcontract: S-789-000-005

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Fall 1988 Thesis 48 units Satisfactory progress

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

During the Fall 1988 semester, I completed the theoretical formulation for a method of recovering phase and amplitude information from observed seismograms. I presented results from this research at the 1988 Fall Meeting of the American Geophysical Union (the abstract from this presentation is attached). I am presently writing a paper on this methodology, to be submitted during the spring semester. I anticipate defending my thesis during the Summer 1989 term.

3. Give brief statement of your involvement with the Geophysics Laboratory Laboratory and Dr. John Sipar.

I have had many interesting discussions with Dr. John Cipar at the Air Force Geophysical Laboratory about my research on polarization anisotropy and the nature of heterogeneity in the Eurasian upper mantle. I am planning on visiting the Laboratory soon to present a seminar on my recent results.

"I certify that all information stated is correct and complete."


Signature/Fellowship Recipient

Lind S. Gee
TYPED NAME/FELLOWSHIP RECIPIENT

The Measurement of Travel Times for Tomography


LIND S. GEE AND THOMAS H. JORDAN

Department of Earth, Atmospheric, and Planetary Sciences,
Massachusetts Institute of Technology, Cambridge, MA 02139

Although the inversion of travel times by tomographic methods is leading to new insights into the deep structure of the earth, the resolution of tomographic data sets based on direct P or S arrivals is limited by the sparse and heterogeneous distribution of seismic sources and receivers. To improve this resolution, we have developed a very general methodology for obtaining the travel times of complex, dispersed wave groups not easily measured by standard techniques, one that takes advantage of our ability to compute realistic synthetic seismograms. To isolate a particular wavegroup, we construct the corresponding synthetic seismogram from a reference earth model, compute its cross-correlation with the observed seismogram, and window this correlation function in the time domain. We recover estimates of the differential phase and amplitude at a discrete set of center frequencies $\{\omega_i : i = 1, \dots, N\}$ by applying a set of narrow-band filters to the windowed cross-correlation function. In the vicinity of ω_i , the observed wavegroup is related to the synthetic wavegroup through a differential response operator that can be parameterized in terms of a differential phase delay $\Delta\tau_p(\omega_i)$, a differential group delay $\Delta\tau_g(\omega_i)$, and a differential attenuation $\Delta\tau_a(\omega_i)$. It can be shown that the filtered cross-correlation function is approximated by $E(t) \cos\Phi(t)$, where $E(t)$ is a Gaussian depending on the filter bandwidths, the window parameters, and $\Delta\tau_g$, and $\Phi(t)$ is a function of $\Delta\tau_p$, $\Delta\tau_g$, and $\Delta\tau_a$, as well as the filter and window parameters. In our procedure, we solve for $\Delta\tau_p$, $\Delta\tau_g$, and $\Delta\tau_a$ by fitting this theoretical expression to the observed cross-correlation function. The parameters are then inverted for earth structure using conventional techniques. The method and its extensions account for the complications of caustic phase shifts, interferences among multiple arrivals, dispersion, attenuation, and differences in polarization. We illustrate these procedures using GDSN data for a variety of Eurasia-crossing paths.

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Ms. Lind Gee is making satisfactory academic progress toward a Ph.D. in the area of Earth Sciences in the discipline of Geophysics for the Fall 1988 semester."


Signature/Advising Professor

Thomas H. Jordan, Professor of Geophysics
TYPED NAME/TITLE OF ADVISING
PROFESSOR

2094t

NEW DATA PROCESSING TECHNIQUES FOR SEISMOLOGICAL STUDIES OF EARTH STRUCTURE

LIND S. GEE AND THOMAS H. JORDAN

Department of Earth, Atmospheric and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, MA 02139

ABSTRACT

We have formulated a new set of waveform-analysis procedures to recover phase and amplitude information from seismograms. The new procedures have a number of advantages over existing techniques, and they appear to be capable of making fundamentally new observations about the structure of the earth's interior. We have used them to measure the travel times and quality factors of body waves, including those imbedded in the complex wavetrains, as well as the dispersion and attenuation of surface waves, including higher modes. In particular, we have applied these techniques to three-component seismograms to investigate the structure of the Eurasian upper mantle.

TABLE OF CONTENTS

ABSTRACT.....	1
TABLE OF CONTENTS.....	2
INTRODUCTION	3
TECHNICAL DISCUSSION.....	5
REFERENCES	18
ACKNOWLEDGMENTS	21

INTRODUCTION

Seismograms recorded by global networks following large earthquakes contain a vast quantity of information about the details of earth structure. A major focus of seismological research concerns methods for extracting this information, understanding its implications, and using it to refine structural models. By employing a series of techniques developed over the last decade, seismologists have made spectacular progress in elucidating the three-dimensional structural variations associated with boundary layers and internal dynamics of the mantle and core [e.g., Dziewonski *et al.*, 1977; Masters *et al.*, 1982; Clayton and Comer, 1983; Dziewonski, 1984; Woodhouse and Dziewonski, 1984; Nataf *et al.*, 1984, 1986; Hager *et al.*, 1985; Creager and Jordan, 1986a,b; Ritzwoller *et al.*, 1986; Dziewonski and Woodhouse, 1987; Jordan *et al.*, 1988]. Only a small fraction of the information available from existing data has been used for this purpose, however, and many important geophysical questions related to the details of earth structure remain unanswered. What is the fine structure of the inner core-outer core transition, the core-mantle boundary, and the mid-mantle transition zone? What are the spectra of lateral heterogeneity at these interfaces, how are they correlated, and how do they differ from the spectra at other levels? What seismological structures are diagnostic of the modulation of mantle convection by chemical, phase and/or viscosity variations within the transition zone? To what degree are the deep-seated thermal and chemical structures of the surficial boundary layers correlated with shallow crustal structures? What aspects of seismic-wave anisotropy are related to present-day mantle flow? Does the near-surface anisotropy of the sub-continental mantle reflect structures frozen into the plates during deformation events in the distant geological past? Is inner-core anisotropy associated with frozen-in structure or active convection?

The continued application of existing techniques to an ever growing catalog of digitally recorded seismograms will no doubt allow seismologists to make further progress on these problems. However, we believe this progress can be greatly accelerated by the introduction of techniques that take advantage of improving capabilities, especially the ever-increasing speed with which large machines can perform signal processing, seismogram synthesis, and inversion calculations. As part of the DARPA-sponsored program in test-ban treaty verification, we have developed an approach to extracting structural information from the seismogram that is novel and promises to deliver fundamentally new constraints on earth structure.

We have formulated a new set of waveform-analysis procedures to recover phase and amplitude information from seismograms. These procedures have a number of advantages over existing methods. Like waveform-inversion techniques, they make use of our ability to compute synthetic seismograms from realistic earth models, and they provide a uniform

methodology for inverting body-wave, surface-wave, and other types of wave groups from three-component data. Unlike waveform-inversion techniques, whose "black-box" character can make interpretation difficult, they isolate from the seismogram time-like quantities that correspond to well-defined scalar-valued functionals of earth structure: phase delays, group delays, attenuation times, and their generalizations. An inversion of these quantities for earth structure (1-D, 2-D or 3-D) can thus be accomplished in a separate step using standard perturbation techniques. By separating the measurement of data functionals from the inversion of the data for earth structure, we facilitate the assessment of the significance and robustness of the measurements, and we allow a variety of model parameterizations and inversion schemes to be compared.

We have implemented these waveform-analysis procedures on the Geophysical Computing System at MIT and have demonstrated that they are capable of making fundamentally new observations about the structure of the earth's deep interior. We have used them to measure the travel times and quality factors of body waves, including those imbedded in the complex wavetrains, as well as the dispersion and attenuation of surface waves, including higher modes. In particular, we have made observations of large-magnitude (~ 10 s) shear-wave splitting in multiply reflected *S* waves propagating across the stable continental platforms of Eurasia.

TECHNICAL DISCUSSION

A seismogram $s(t)$ can be represented as a sum over waveforms $\{u_n(t) : n = 1, 2, \dots\}$:

$$s(t) = \sum_{n=0}^{\infty} u_n(t) \quad (1)$$

The seismologist may choose a particular element $u_n(t)$ to be a body-wave pulse, a surface-wave group, or any other convenient representation of the seismic wavetrain [Aki and Richards, 1980]. The classical approach is to separate the process of measuring waveform properties from the process of inverting for earth structure. Discrete body-wave arrivals are identified and their travel times and attenuation factors are determined; surface-wave groups are isolated and their dispersion and attenuation properties are measured. These data are then inverted for an earth model whose parameterization is sufficiently complete to explain the observed variations. If a sufficiently good starting model is available, the latter step can be accomplished using a perturbation theory based on the variational principles of Fermat and Rayleigh (Figure 1).

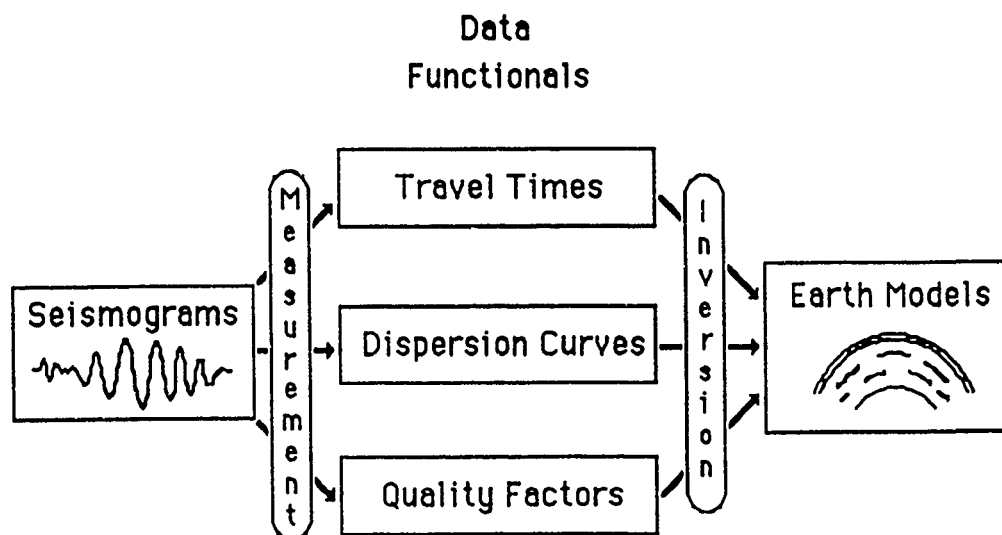


Figure 1. "Classical" seismological methodology breaks the problem of determining earth structure into two parts: (1) the measurement of well-defined data functionals--e.g., the travel times of body phases; phase and group velocities of surface waves--and (2) the inversion of these data for earth models.

A problem with this approach concerns the various wave effects that complicate the measurement of individual wave groups. In the case of body-wave travel times, these include caustic phase shifts, diffraction effects, and the physical dispersion associated with attenuation. In the case of surface-wave dispersion, they involve source-related phase shifts and the problems associated with isolating individual modes. Indeed, for portions of the seismogram where many wave groups arrive simultaneously, the waveforms cannot generally be resolved into either individual body waves or surface waves, and the classical measurement schemes that rely on waveform isolation can fail to produce reliable results. Techniques based on frequency-wavenumber filtering have been used to separate interfering surface waves [Nolet, 1975, 1977; Cara, 1979; Cara *et al.*, 1980], but they generally require large-aperture arrays of seismometers not common in global studies of earth structure.

Many of these difficulties can be avoided by inverting the complete seismogram directly for earth structure. In the ideal situation where the entire wavefield is recorded by a spatially dense set of receivers from a spatially dense set of sources, powerful nonlinear inversion techniques can be applied to recover an image of the three-dimensional structure [A. Tarantola, personal communication, 1988]. Although the collection of these sorts of ideal data sets can be approached in exploration seismology, where the effort and resources concentrated on imaging small volumes of the earth are high, the data sets available to global seismology are limited by the distribution of large-magnitude sources, primarily earthquakes, and the sparse distribution of stations, especially those with high-quality, digitally recording seismometers. In this situation, fully nonlinear methods cannot be applied because the solution manifolds have multiple minima, and we are forced to linearize the problem by assuming the solution to the waveform-inversion problem is in some sense close to a chosen reference earth structure.

Theoretical and computational advances over the last two decades now permit the routine calculation of synthetic seismograms $\tilde{s}(t)$ using a variety of waveform representations. As in the case of equation (1), a seismogram computed from a reference earth model m_0 can be written as a sum over synthetic waveforms $\{\tilde{u}_n(t)\}$:

$$\tilde{s}(t) = \sum_{n=0}^N \tilde{u}_n(t) \quad (2)$$

although the number of elements in the sum, N , must necessarily be finite. Synthetic seismograms accurately model wave propagation through realistic earth structures, as well as source excitation effects. Most waveform-inversion algorithms [e.g., Lerner-Lam and Jordan, 1983, 1987; Dziewonski and Steim, 1983; Woodhouse and Dziewonski, 1984] subtract synthetic seismograms computed for the reference structure from the observed time series to form differential seismograms that are then inverted for a structural perturbation

using first-order perturbation theory (Figure 2). This linearized inverse problem thus takes the form

$$G \delta m = \delta s \quad (3)$$

where δs is a vector containing the differential time series, δm is the model perturbation, and G is a matrix of partial derivatives.

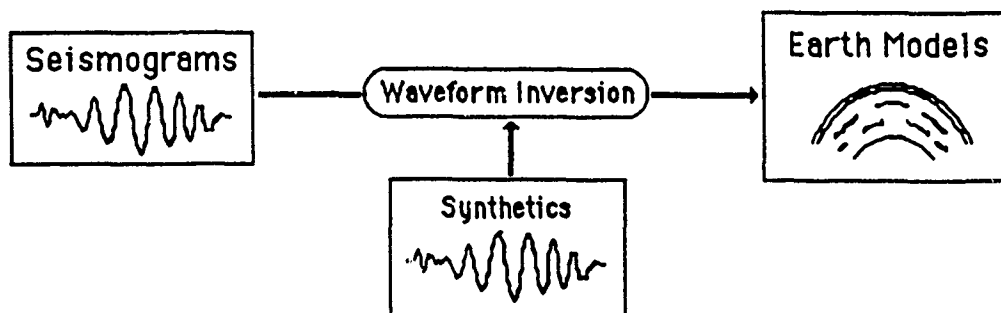


Figure 2. The more modern methodology of waveform inversion computes the differences between the observed seismograms and synthetic seismograms and inverts these differential seismograms directly for earth structure.

The primary problem with waveform inversion is its "black-box" character: it is difficult to evaluate exactly what features on the seismograms are being used to determine what features of the earth model. Waveform inversion allows more information on the seismogram to be used in constraining earth structure, but the information is of uneven quality. Amplitude and phase information gets all mixed up, so understanding the robustness of the solution to departures from the modeling assumptions (which are usually incomplete with respect to first-order amplitude perturbations) is often impossible. Moreover, the results can be very sensitive to how the data are weighted, and the resolving power of any particular data set is hard to assess. For example, it is not easy for a seismologist to know how much of the residual contained in a differential seismogram is ascribable to a one-dimensional path-averaged perturbation, as opposed to two- or three-dimensional along-path and off-path perturbations.

For the last several years, one goal of our research program has been to improve automated techniques for recovering information from seismograms. Our first efforts were directed at developing waveform-inversion algorithms [Lerner-Lam and Jordan, 1983, 1987]. In particular, we introduced matched-filtering techniques that isolated higher-mode information prior to inversion and thus facilitated the understanding of what information on the seismograms is most significant in constraining the solution. We used our ability to manipulate this information to set up various weighting schemes and investigated how they

affected the resolving power of the waveform data [Gee *et al.*, 1985]. By applying these techniques to a series of paths crossing the western Pacific Ocean and the Eurasian continent, we were able to demonstrate that the higher-mode data are inconsistent with models that confine continent-ocean heterogeneity to depths less than about 220 km [Lerner-Lam and Jordan, 1987].

We have recently developed a new set of techniques for extracting information from the seismogram, which are as yet unpublished although several papers are in the final stages of preparation. Like the waveform-inversion method of Lerner-Lam and Jordan [1983], they make use of the cross-correlation between waveform synthetics and the observed seismograms to isolate structural information. However, the way this information is recovered from the seismogram and then inverted for earth models is very different (Figure 3).

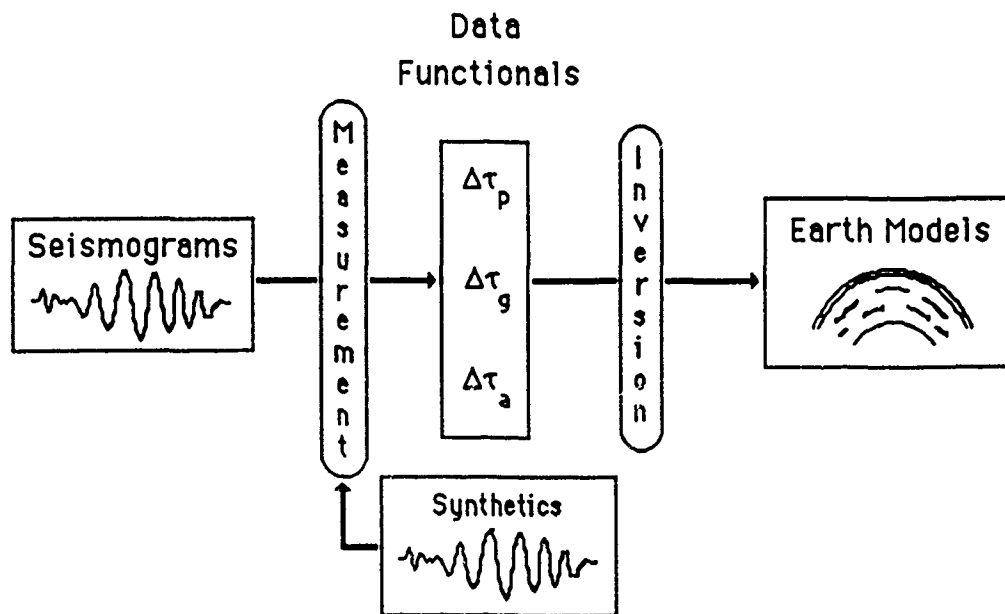


Figure 3. The methodology discussed in this proposal combines the advantages of the classical approach with those of waveform inversion. Measurements of time-like data functionals are made using synthetic seismograms to account for wave effects; e.g., caustic phase shifts, dispersion, and diffraction. These data are subsequently inverted for earth models. By separating the measurement process from the inversion process, the significance of the data and the robustness of the modeling can be more easily assessed than in a one-step, "black-box" waveform inversion scheme. The technique provides a uniform methodology for inverting body-wave, surface-wave, and other types of wave groups from three-component data. For the definitions of the data functionals $\Delta\tau_p$, $\Delta\tau_g$, and $\Delta\tau_a$, see equation (13).

Our technique is best described in the context of a simple numerical experiment. Consider the two continental structures illustrated in Figure 4: SNA, a model of stable North America which Grand and Helmberger [1984] derived by fitting *SH*-polarized

The specific problem we pose is to estimate the Love-wave dispersion of SNA using EU2 as a reference model.

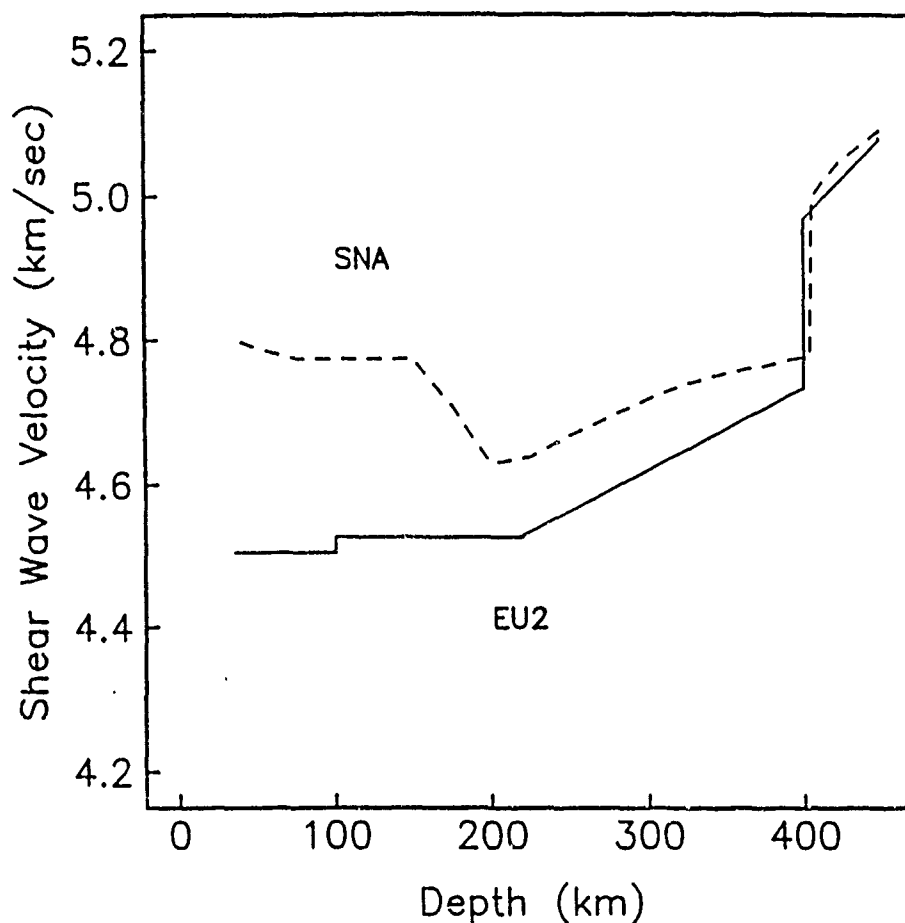


Figure 4. Shear velocity as a function of depth for continental upper mantle models EU2 [Lerner-Lam and Jordan, 1987] and SNA [Grand and Helmberger, 1984]. SNA (dashed line) was derived from fitting multiply reflected SH-polarized waveforms for stable North America paths; EU2 (solid line) was derived from waveform inversion of fundamental Rayleigh waves and PSV-polarized higher modes for northern Eurasia. SNA has significantly higher velocities than EU2 in the upper 400 km; the discrepancy between these models is due in part to path differences and in part to strong polarization anisotropy in the upper mantle [Lerner-Lam and Jordan, 1987; Gee and Jordan, 1988].

The basis for our waveform-analysis method is the construction of an "isolation filter" $\tilde{f}(t)$, which we define as a weighted sum over synthetic waveforms:

$$\tilde{f}(t) = \sum_{n=0}^N \alpha_n \tilde{u}_n(t) \quad (4)$$

For standard measurements of surface-wave dispersion and body-wave travel times, we usually take the coefficients α_n to be zero for all but one value of n ; i.e., we choose the isolation filter to be the waveform of interest. In the case of the problem posed above, therefore, $\tilde{f}(t)$ is simply the fundamental-mode Love wave, which we calculate from the reference model EU2. Examples of transverse-component synthetics corresponding to an earthquake in Kamchatka (83/08/17, $h = 77$ km) recorded at the ASRO station KONO in Norway ($\Delta = 63^\circ$) are plotted in Figure 5a.

The autocorrelation function of $\tilde{f}(t)$ is defined by

$$C_{\tilde{f}\tilde{f}}(t) = \tilde{f}(t) \otimes \tilde{f}(t) \equiv \int_{-\infty}^{\infty} \tilde{f}(\tau) \tilde{f}(\tau+t) d\tau \quad (5)$$

$C_{\tilde{f}\tilde{f}}(t)$ is a symmetric function peaked at zero lag (Figure 5b) whose real-valued Fourier spectrum $C_{\tilde{f}\tilde{f}}(\omega)$ is the squared modulus of the complex Fourier spectrum $\tilde{f}(\omega)$. Before proceeding further, it will be useful to develop the properties of this autocorrelation function in terms of a set of special functions known as Hermite functions, which are defined to be the product of an unnormalized Gaussian, $G(x) \equiv \exp(-x^2/2)$, and a Hermite polynomial of degree k , $He_k(x)$ [Szegő, 1959]. These functions play an important role in the theory that underlies our method. We expand the spectrum on the positive ω -axis in terms of Hermite functions:

$$C_{\tilde{f}\tilde{f}}(\omega) H(\omega) = G\left(\frac{\omega - \omega_f}{\sigma_f}\right) \sum_{k=0}^{\infty} f_k He_k\left(\frac{\omega - \omega_f}{\sigma_f}\right) \quad (6)$$

In this expression, $H(\omega)$ is the Heaviside step function. Hermite polynomials are defined by the expression

$$He_k(x) = k! \sum_{j=0}^{[k/2]} \frac{(-1)^j x^{k-2j}}{2^j j! (k-2j)!} \quad (7)$$

Sansone [1959] and Szegö [1959] give further definitions and properties; in particular, on the interval $(-\infty, \infty)$ the functions $\{He_k(x) : k = 0, 1, 2, \dots\}$ are complete and orthogonal with respect to the Gaussian weight $G(x)$. The coefficients in (6) are given by

$$f_k = \frac{1}{k! \sqrt{2\pi} \sigma_f} \int_0^\infty C_{\mathcal{F}\mathcal{F}}(\omega) He_k\left(\frac{\omega - \omega_f}{\sigma_f}\right) d\omega \quad (8)$$

An expansion of $C_{\mathcal{F}\mathcal{F}}(\omega)$ in terms of Hermite functions has two advantages. First, the convenient Fourier-transform properties of Hermite functions [Szegö, 1959] yield a simple series expression for its time-domain image:

$$C_{\mathcal{F}\mathcal{F}}(t) = \sqrt{2/\pi} \sigma_f G(\sigma_f t) [(f_0 - f_2 \sigma_f^2 t^2 + f_4 \sigma_f^4 t^4 - \dots) \cos \omega_f t - (f_1 \sigma_f t - f_3 \sigma_f^3 t^3 + f_5 \sigma_f^5 t^5 - \dots) \sin \omega_f t] \quad (9)$$

Second, because $C_{\mathcal{F}\mathcal{F}}(\omega)$ is expected to be peaked in the pass-band of the instrument response, (9) can usually be approximated by its first few terms. We can always choose the location parameter ω_f such that $f_1 = 0$, and the scale parameter σ_f such that $f_2 = 0$. Therefore, if terms of third and higher order can be neglected, then we obtain the standard "wave-packet" approximation [e.g., Bracewell, 1978]:

$$C_{\mathcal{F}\mathcal{F}}(t) = E(t) \cos \Phi(t) \quad (10)$$

where $E(t) = \sqrt{2/\pi} f_0 \sigma_f G(\sigma_f t)$ and $\Phi(t) = \omega_f t$. In other words, the autocorrelation function of the isolation filter can be represented as a cosinusoidal "carrier" modulated by a Gaussian "envelope". The carrier frequency is the center frequency of the response, ω_f , and the half-width of the envelope is the inverse of the half-bandwidth, σ_f . Because equation (10) corresponds to taking the spectrum $C_{\mathcal{F}\mathcal{F}}(\omega)$ to be a Gaussian with $\sigma_f \ll \omega_f$, we refer to it as the "Gaussian narrow-band approximation".

Figure 5b shows the good agreement between the actual autocorrelation function computed for the ASRO response to the Love wave (solid line) and that obtained from the narrow-band approximation (dotted line). In this comparison, the parameters of the Gaussian were computed from the first three polynomial moments of the spectrum.

Now consider the cross-correlation between the isolation filter and the complete synthetic seismogram, $C_{\mathcal{F}\mathcal{S}}(t) = \tilde{f}(t) \otimes \tilde{s}(t)$, and the cross-correlation between the isolation filter and the observed seismogram, $C_{\mathcal{F}s}(t) = \tilde{f}(t) \otimes s(t)$. If the isolation filter corresponds to a single waveform that is reasonably well separated from other energy on the

seismogram, then $C\tilde{f}_s(t)$ will closely approximate $C\tilde{f}_f(t)$ near zero lag. Figure 5b shows that this is indeed the case for our Love-wave example. $C\tilde{f}_s(t)$, on the other hand, will not be the same as $C\tilde{f}_f(t)$ because of differences in propagation, which we hope to measure, as well as differences between the actual and assumed source mechanisms, which we ignore, at least for the present discussion. (In practice, we have generally found the Harvard CMT solutions to be adequate for the sorts of modeling we propose here; when they are not, we have the capability to determine our own moment-tensor solutions.) We suppose the actual waveform f has a spectrum that is related to the synthetic \tilde{f} by a differential response operator D :

$$f(\omega) = D(\omega)\tilde{f}(\omega) \quad (11)$$

We write the differential response in the form $D(\omega) = D_0 e^{i\Delta k(\omega)x}$, where D_0 is a real-valued constant, x is the propagation distance, and $\Delta k(\omega) \equiv k(\omega) - \tilde{k}(\omega)$ is the complex-valued differential wavenumber. We expand the latter in a Taylor series about the center frequency ω_f :

$$\Delta k(\omega) = \Delta k(\omega_f) + (\omega - \omega_f) \Delta k'(\omega_f) + \frac{(\omega - \omega_f)^2}{2} \Delta k''(\omega_f) + \dots \quad (12)$$

If the differential dispersion is sufficiently weak across the band $\omega_f \pm \sigma_f$, then we can neglect terms of order higher than the first, and (12) becomes

$$\Delta k(\omega) = x^{-1} [\omega_f \Delta \tau_p(\omega_f) + (\omega - \omega_f) \Delta \tau_g(\omega_f) + i(\omega - \omega_f) \Delta \tau_a] \quad (13)$$

$\Delta \tau_p(\omega_f)$ is the differential phase delay at the center frequency ω_f ; $\Delta \tau_g(\omega_f)$ is the differential group delay; and $\Delta \tau_a(\omega_f)$ is a differential amplitude factor. In the case where the differential amplitude is due solely to attenuation, $\Delta \tau_a(\omega_f)$ is the difference between the actual and reference values of t^* , defined to be the travel time divided by twice the quality factor Q .

Under the linear dispersion approximation (13) we can obtain closed-form expressions for the coefficients of a complete Hermite-function expansion of $C\tilde{f}_f(t)$. Since the expressions are fairly complicated, we do not reproduce them here. Instead, we give explicit formulae for the Gaussian narrow-band approximation, $C\tilde{f}_f(t) = E(t) \cos \Phi(t)$:

$$E(t) = \sqrt{2/\pi} f_0 \sigma_f D_0 e^{\sigma_f^2 \Delta \tau_a^2 / 2} G(\sigma_f (t - \Delta \tau_g)) \quad (14a)$$

$$\Phi(t) = \omega_f (\Delta \tau_p - t) - \sigma_f^2 \Delta \tau_a (\Delta \tau_g - t) \quad (14b)$$

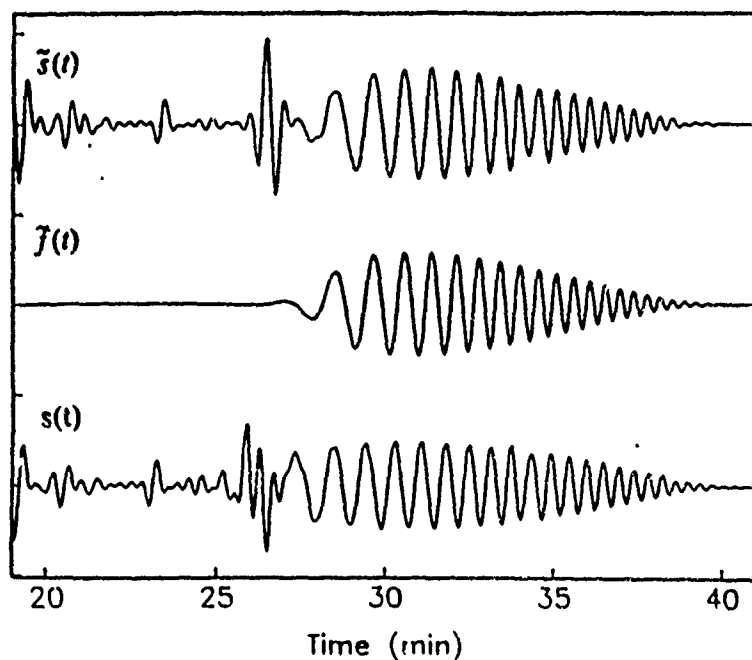


Figure 5a. Transverse component synthetic seismograms calculated from models EU2 and SNA for a Kamchatka event (83/08/18, $h=77\text{km}$) recorded at the ASRO station KONO. $\tilde{s}(t)$ is the seismogram calculated from EU2; $s(t)$ is the seismogram calculated from SNA. $\tilde{f}(t)$ is the isolation filter for the Love wave, calculated from EU2. All three synthetic seismograms were calculated by normal mode summation and are complete to 50 mHz. For $\tilde{s}(t)$ and $s(t)$, this represents a sum of over 16000 modes; for $\tilde{f}(t)$ a sum over 500 modes.

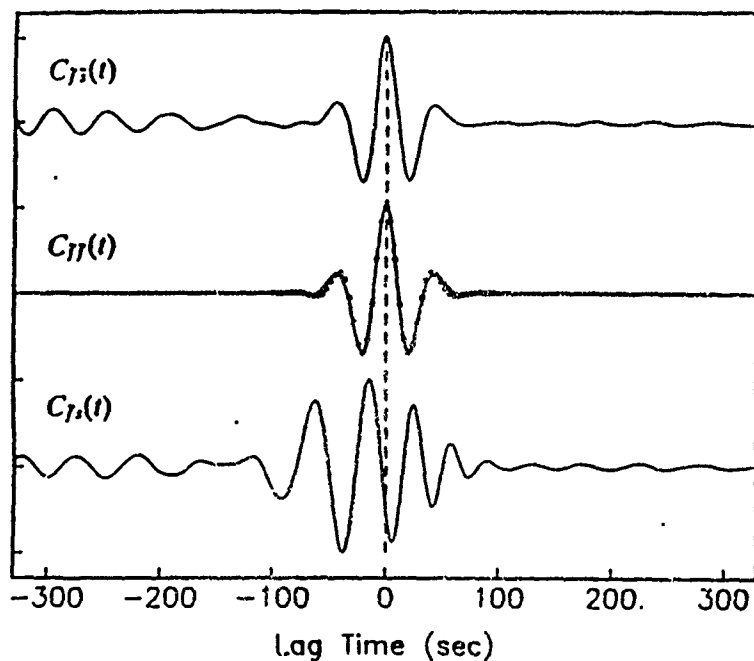


Figure 5b. $C_{\tilde{s}\tilde{s}}(t)$, $C_{\tilde{f}\tilde{f}}(t)$, and $C_{\tilde{s}\tilde{f}}(t)$ calculated from the seismograms in Figure 5a. $C_{\tilde{f}\tilde{f}}(t)$ is a symmetric function, peaked at zero lag. The dotted line is the Gaussian narrow-band approximation to $C_{\tilde{f}\tilde{f}}(t) = E(t) \cos \omega_f t$ (equation 10); in this example, ω_f is 23 mHz and σ_f is 6.2 mHz. The Gaussian narrow-band approximation is valid near zero lag. If the waveform of interest is isolated in the time domain, then $C_{\tilde{s}\tilde{s}}(t) = C_{\tilde{f}\tilde{f}}(t)$ near zero lag, which is the case in this example. However, $C_{\tilde{s}\tilde{s}}(t)$ will not in general be the same as $C_{\tilde{f}\tilde{f}}(t)$ due to differences in propagation, which we hope to measure, as well as differences in actual and assumed source mechanisms, which we presently ignore.

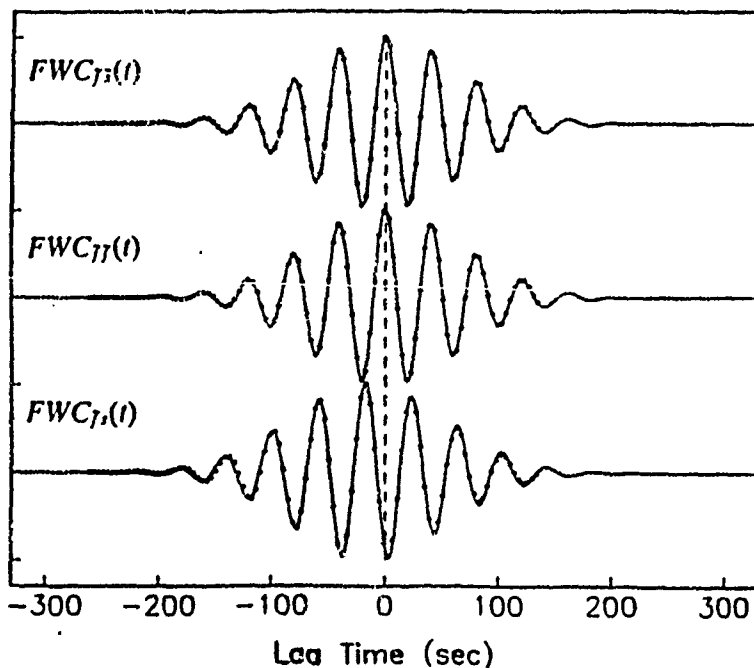


Figure 5c. Comparisons between the calculated filtered windowed cross-correlation functions $F_i W C_{\tilde{s}\tilde{s}}(t)$, $F_i W C_{\tilde{f}\tilde{f}}(t)$, and $F_i W C_{\tilde{s}\tilde{f}}(t)$, given by the solid line, and the functions obtained by fitting the analytic expressions for the Gaussian approximation for a filter with a center frequency of 25 mHz and bandwidth of 2.5 mHz, given by the dotted line. The fit of the Gaussian approximation to the observed values, which is excellent, determines the values of $\Delta\tau_p$, $\Delta\tau_g$, and $\Delta\tau_a$ (equation 13).

It is possible to fit the narrow-band expression to the observed function $C\tilde{\gamma}_s(t)$ and thereby determine the values of $\Delta\tau_p(\omega_f)$, $\Delta\tau_g(\omega_f)$, and $\Delta\tau_a(\omega_f)$. For the case at hand, however, the results are poor, primarily because the differential dispersion is sufficiently strong that equation (13) does not provide an adequate approximation across the entire bandwidth of the ASRO instrument response.

We could, of course, pre-filter the seismograms in narrow bands of our choosing and thus enforce the weak-dispersion approximation, but this spreads the energy over the time series and increases the interference with other waveforms. For this reason, we include two additional steps in our processing: (1) We first apply a Hanning taper of half-width σ_w^{-1} centered at a reference time t_w to the cross-correlation function, yielding a windowed cross-correlation function $WC\tilde{\gamma}_s(t)$. (2) We then apply to $WC\tilde{\gamma}_s(t)$ a series of narrow-band filters $\{F_i : i = 1, \dots, I\}$ with varying center frequencies ω_i and half-bandwidths $\sigma_i \ll \omega_i$, yielding the filtered, windowed cross-correlation functions $F_i WC\tilde{\gamma}_s(t)$. Windowing the broad-band correlation function prior to narrow-band filtering allows the full bandwidth to be used to separate the waveform of interest from other interfering arrivals. This procedure has been previously employed in residual-dispersion and phase-matched filtering analysis [Dziewonski *et al.*, 1972; Herrin and Goforth, 1977, 1986], to which our techniques are closely related.

We have obtained closed-form formulae for the Hermite-function coefficients that allow each $F_i WC\tilde{\gamma}_s(t)$ to be computed to arbitrary accuracy, but even the equations for the Gaussian approximation are sufficiently complicated that we do not give them here. These expressions depend upon a number of quantities that are either known (the four parameters t_w , σ_w , ω_i , and σ_i) or can be determined by fitting the Gaussian expressions to the synthetic autocorrelation function (the parameters ω_f and σ_f), and three quantities that depend on the differential response (the observables $\Delta\tau_p(\omega'_i)$, $\Delta\tau_g(\omega'_i)$, and $\Delta\tau_a(\omega'_i)$). The latter are functions of the effective center frequency

$$\omega'_i = \frac{\omega_f \sigma_i^2 + \omega_i (\sigma_f^2 + \sigma_w^2)}{\sigma_f^2 + \sigma_w^2 + \sigma_i^2} \quad (15)$$

and can be estimated by fitting the Gaussian approximation to the observed time series $F_i WC\tilde{\gamma}_s(t)$.

Figure 5c displays the results of this waveform-analysis procedure to our Love-wave example. The fit obtained is excellent, and the phase and group delays recovered from it are close to the theoretical values (the attenuation structure was not perturbed). The results for center frequencies varying from 13 to 42 mHz for both Love and Rayleigh waves from this single station are plotted against the theoretical values in Figure 6. Additional synthetic

tests have been done to assess the performance of the method in recovering body-wave travel times, including times from triplicated branches, and quality factors (see Figure 7). Formal errors in the observed times are easily derived from the waveform fits, and we will include this uncertainty analysis into our automated procedures.

The observables $\Delta\tau_p$, $\Delta\tau_g$, and $\Delta\tau_a$ are functionals of earth structure. In the case where the isolation filter $\tilde{f}(t)$ is a single waveform, the Fréchet kernels are known [Aki and Richards, 1980]. Hence, once they have been measured and their uncertainties determined as a function of frequency (and source-receiver position) by fitting the Gaussian narrow-band expressions to $F_iWC\tilde{f}_s(t)$, they are easily inverted for structural models using standard linearized methods. If the interference by other waveforms is not severe, this inversion can be accomplished independently of the measurement. If the interference is significant, so that $C\tilde{f}\tilde{f}(t)$ is not a good approximation to $C\tilde{f}_s(t)$ near zero lag, then we can correct the measurements by the values of the parameters determined from $F_iWC\tilde{f}_s(t)$. If it is really severe, so that these corrections are themselves inaccurate, then it may be necessary to proceed by iterating between the data analysis and the data inversion. We have thus far not encountered examples where this is required.

It is important to note that we do not require that the isolation filters $\tilde{f}(t)$ accurately model the waveforms they are intended to represent, so long as we have available a complete synthetic seismogram $\tilde{s}(t)$ that does. In our applications, we generally compute $\tilde{s}(t)$ by complete normal-mode summation (regularly up to 50 mHz for *PSV* components and 100 mHz for *SH*), whereas we use approximate ray-theoretic methods (e.g., WKBJ) to calculate the isolation filters for body waves. We then employ the differential phase and group delays computed from $FWC\tilde{f}_s(t)$ to correct the observations for inaccuracies in the ray-theoretic approximations. Using this hybrid capability, we can thus combine the computational efficiency and theoretical insight offered by asymptotic traveling-wave representations with the computational accuracy and uniform methodology afforded by normal-mode summation.

We have applied these techniques to the study of upper-mantle structure beneath the Eurasian and North American continents. Some highlights of the Eurasian results have been recently published in a short note to *Geophysical Research Letters* [Gee and Jordan, 1988], which is reproduced here as an appendix. In particular, by treating waveforms of differing polarizations using a uniform methodology we have been able to observe shear-wave splitting as large as 10 s on *S* waves multiply reflected beneath the Siberian and Russian platforms (see Figures 8 and 9).

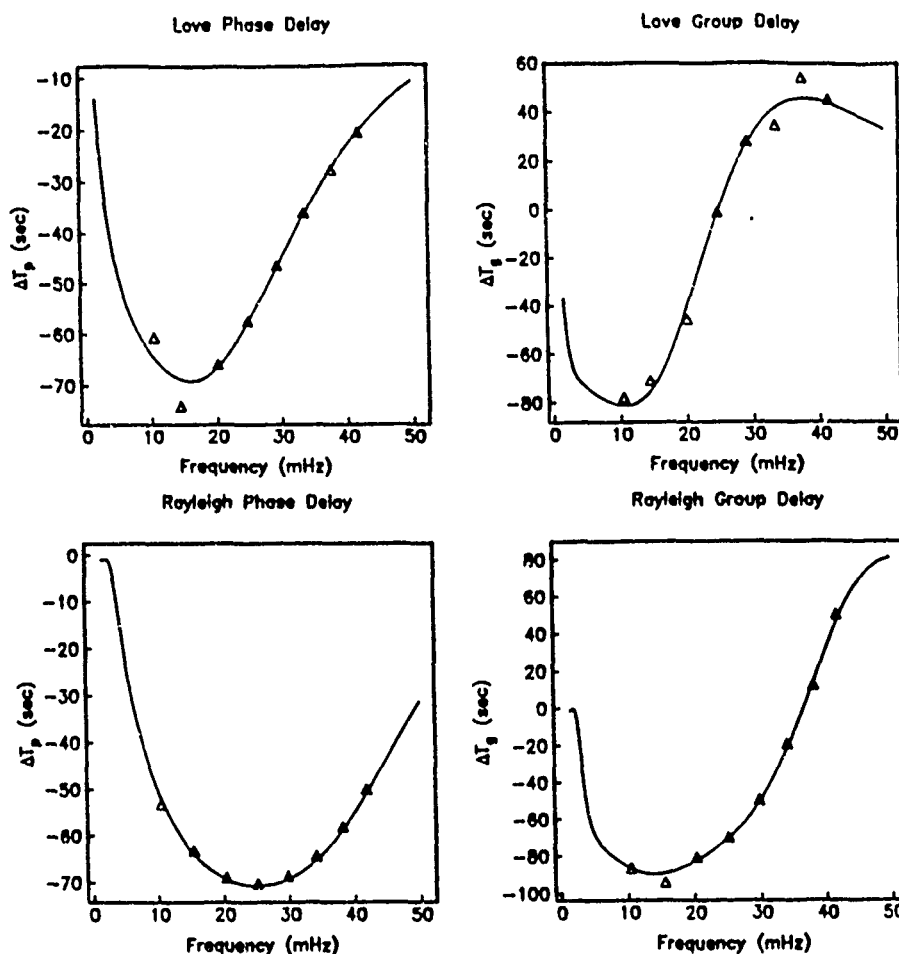


Figure 6. Estimates of $\Delta\tau_p(\omega_i')$ and $\Delta\tau_g(\omega_i')$ (attenuation structure was not perturbed) recovered using this waveform analysis procedure for fundamental Love and Rayleigh waves (triangles) compared to the theoretical values for SNA-EU2 (solid lines). In general, the agreement between the actual and estimated values are very good, although there is more scatter in the Love wave dispersion due to the greater interference from higher modes (see Figure 5a).

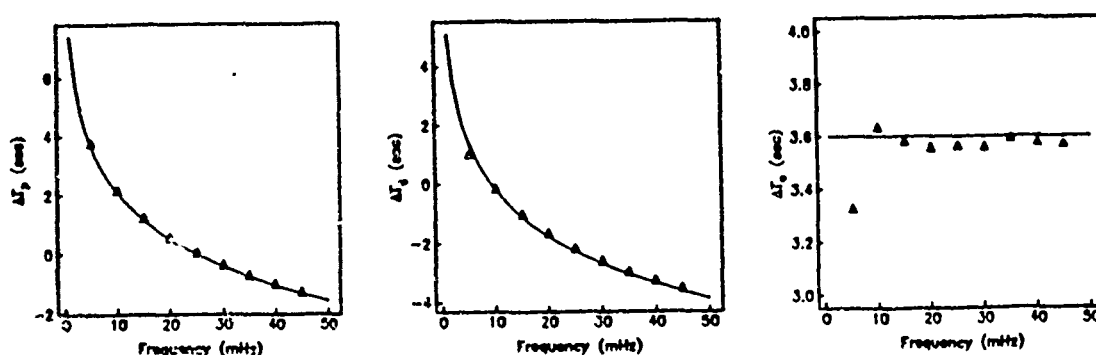


Figure 7. Estimates of $\Delta\tau_p(\omega_i')$, $\Delta\tau_g(\omega_i')$, and $\Delta\tau_a(\omega_i')$ recovered from a numerical experiment in which the "observed seismograms" were calculated from a model having a linear, causal, constant Q and the isolation filter was calculated from a reference model having no intrinsic attenuation. Estimates of $\Delta\tau_p(\omega_i')$, $\Delta\tau_g(\omega_i')$, and $\Delta\tau_a(\omega_i')$ (triangles) compare favorably with the theoretical values (solid line).

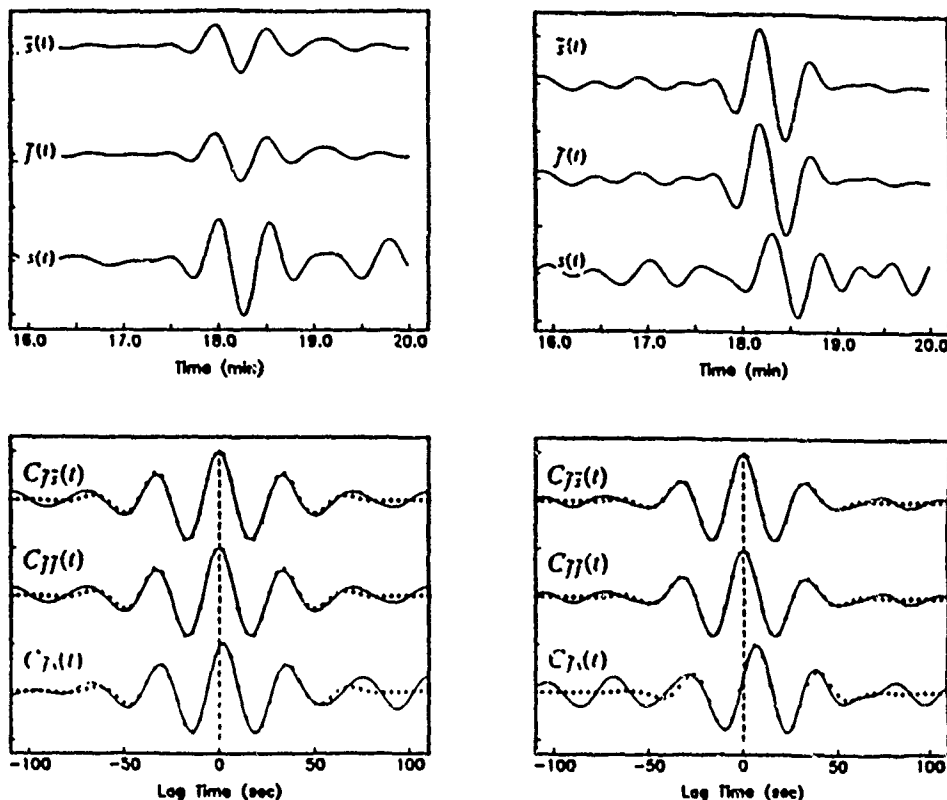


Figure 8. Application of the waveform analysis procedures to shear-wave splitting in Eurasia. a) contains the observed transverse component seismogram recorded at KONO for a Hindu Kush earthquake (84/07/01, $h = 199$ km); the complete synthetic seismogram and the isolation filter for SS, calculated from SNA. b) contains the observed vertical component and the appropriate synthetic seismograms. c) and d) display the correlation functions for the transverse and vertical seismograms. We have estimated $\Delta\tau_p^{SH}(30 \text{ mHz}) = 2.1 \pm 1.0$ s and $\Delta\tau_p^{SV}(30 \text{ mHz}) = 6.3 \pm 1.0$ s. Thus, the total apparent splitting time for SS is $\Delta\tau_{SS} = \Delta\tau_p^{SH} - \Delta\tau_p^{SV}$ is 4.2 ± 1.4 s.

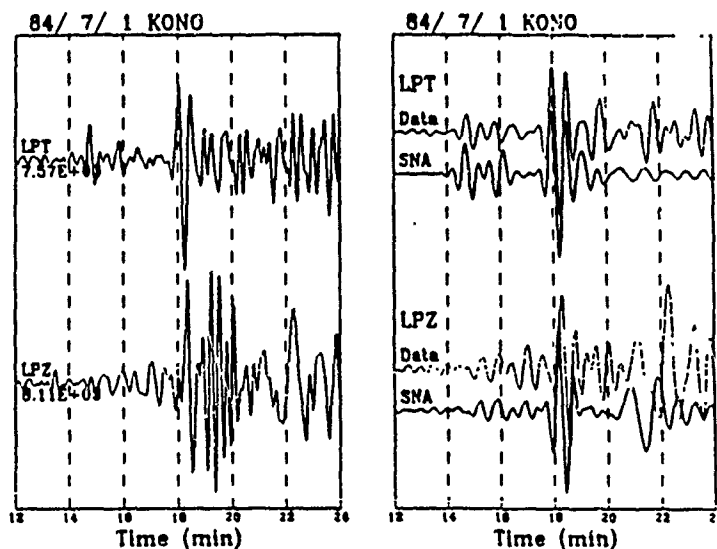


Figure 9. Raw observed vertical and transverse component seismograms (left panel) and filtered synthetic and data (right panel). The apparent shear-wave splitting is dramatically shown by the data-synthetic comparisons, but is also striking in the unfiltered data. For further discussion of these and other observations of shear-wave splitting in Eurasia, see the Appendix.

REFERENCES

- Aki, K., and P. Richards, Quantative Seismology, vol 1., Freeman and Co., San Francisco, 557p., 1980.
- Cara, M., Lateral variations of *S* velocity in the upper mantle from higher Rayleigh modes, *Geophys. J. R. Astr. Soc.*, *57*, 649-670, 1979.
- Cara, M., A. Nercessian, and G. Nolet, New inferences from higher mode data in western Europe and northern Eurasia, *Geophys. J. R. Astr. Soc.*, *61*, 459-478, 1980.
- Clayton, R. W., and R. P. Comer, A tomographic analysis of mantle heterogeneities from body wave travel times (abstract), *EOS. Trans. AGU*, *62*, 776, 1983.
- Creager, K. C., and T. H. Jordan, Slab penetration into the lower mantle beneath the Mariana and other Island Arcs of the Northwest Pacific, *J. Geophys. Res.*, *91*, 3573-3589, 1986a.
- Creager, K.C., and T.H. Jordan, Aspherical structure of the core-mantle boundary from PKP travel times, *Geophys. Res. Lett.*, *13*, 1497-1500, 1986b.
- Dziewonski, A. M., Mapping the lower mantle: Determination of lateral heterogeneity in *P*-velocity up to degree and order 6, *J. Geophys. Res.*, *89*, 5929-5952, 1984.
- Dziewonski, A. M., and D. L. Anderson, Preliminary reference Earth model, *Phys. Earth Planet. Inter.*, *25*, 297-356, 1981.
- Dziewonski, A. M., and F. Gilbert, Observations of normal modes for 84 recordings of the Alaskan earthquake of 1964 March 28. Part II: Further remarks based on new spheroidal overtone data, *Geophys. J. R. Astr. Soc.*, *35*, 401-437, 1973.
- Dziewonski, A. M., and J. M. Steim, Dispersion and attenuation of mantle waves through waveform inversion, *Geophys. J. R. Astr. Soc.*, *70*, 503-527, 1982.
- Dziewonski, A. M., and J. H. Woodhouse, Global images of the Earth's interior, *Science*, *236*, 37-48, 1987.
- Dziewonski, A. M., J. Mills, and S. Bloch, Residual dispersion measurement - a new method of surface-wave analysis, *Bull. Seis Soc. Am.*, *62*, 129-139, 1972.
- Dziewonski, A. M., B. H. Hager, and R. J. O'Connell, Large-scale heterogeneities in the lower mantle, *J. Geophys. Res.*, *82*, 239-255, 1977.
- Gee, L. S., A. L. Lerner-Lam, and T. H. Jordan, Resolving power of higher-mode waveform inversion for Eurasian upper-mantle structure, *AFGL Technical Report 85-0206*, Air Force Geophysical Laboratory, Cambridge, pp. 11-36, 1985.
- Gee, L. S., and T. H. Jordan, Polarization anisotropy and fine-scale structure of the Eurasian upper mantle, *Geophys. Res. Lett.*, *15*, 824-827, 1988.
- Giardini, D., X.-D. Li, and J. H. Woodhouse, Three-dimensional structure of the Earth from splitting in free-oscillation spectra, *Nature*, *325*, 405-411, 1987.
- Grand, S. P., and D. V. Helmberger, Upper mantle shear structure of North America, *Geophys. J. R. Astr. Soc.*, *76*, 399-438, 1984.

- Hager, B. H., R. W. Clayton, M. A. Richards, R. P. Comer, and A. M. Dziewonski, Lower mantle heterogeneity, dynamic topography and the geoid, *Nature*, 313, 541-545, 1985.
- Herrin, E., and T. Goforth, Phase-matched filters: application to the study of Rayleigh waves, *Bull. Seis Soc. Am.*, 67, 1259-1275, 1977.
- Herrin, E., and T. Goforth, Phase analysis of Rayleigh waves from the Shagan River test site in the USSR, *Bull. Seis Soc. Am.*, 76, 1739-1754, 1977.
- Julian, B. R., D. Davies, and R. M. Sheppard, PKJKP, *Nature*, 235, 317-318, 1972.
- Jordan, T. H., A. L. Lerner-Lam, and K. C. Creager, Seismic imaging of boundary layers and deep mantle convection, in *Mantle Convection*, ed. W. R. Peltier, in press, 1988.
- Lerner-Lam, A. L., and T. H. Jordan, Earth structure from fundamental and higher-mode waveform analysis, *Geophys. J. R. Astr. Soc.*, 75, 759-797, 1983.
- Lerner-Lam, A. L., and T. H. Jordan, How thick are the continents?, *J. Geophys. Res.*, 92, 14007-14026, 1987.
- Leveque, J. J., and M. Cara, Long-period Love wave overtone data in North America and the Pacific Ocean: new evidence for upper mantle anisotropy, *Phys. Earth Planet. Inter.*, 33, 164-179, 1983.
- Masters, G., and F. Gilbert, Structure of the inner core inferred from observations of its spheroidal shear modes, *Geophys. Res. Lett.*, 8, 569-571, 1981.
- Masters, G., T. H. Jordan, P. G. Silver, and F. Gilbert, Aspherical earth structure from fundamental spheroidal-mode data, *Nature*, 298, 609-613, 1982.
- Nataf, H.-C., I. Nakanishi, and D. L. Anderson, Anisotropy and shear-velocity heterogeneities in the upper mantle, *Geophys. Res. Lett.*, 11, 109-112, 1984.
- Nataf, H.-C., I. Nakanishi, and D. L. Anderson, Measurements of mantle wave velocities and inversion for lateral heterogeneities and anisotropy, 3, Inversion, *J. Geophys. Res.*, 91, 7261-7307, 1986.
- Nolet, G., Higher Rayleigh modes in wester Europe, *Geophys. Res. Lett.*, 2, 60-62, 1975.
- Nolet, G., The upper mantle structure under western Europe inferred from the dispersion of Rayleigh modes, *J. Geophys.*, 43, 265-285, 1977.
- Revenaugh, J., and T. H. Jordan, Observations of first-order mantle reverberations, *Bull. Seis Soc. Am.*, 77, 1704-1717, 1987.
- Revenaugh, J., and T. H. Jordan, A study of mantle layering beneath the western Pacific, *J. Geophys. Res.*, in press, 1989.
- Ritzwoller, M., G. Masters, and F. Gilbert, Observations of anomalous splitting and their interpretation in terms of aspherical structure, *J. Geophys. Res.*, 91, 10203-10228, 1986.
- Sansone, G., Orthogonal functions, *Pure and Applied Mathematics*, vol. IX, Intersciences Publishers, New York, 411p, 1959.
- Szegő, G., Orthogonal Polynomials, American Mathematical Society Colloquim Publications, vol. 23, American Mathematical Society, Providence, 421p., 1959.
- Widmer, R., G. Masters, and F. Gilbert, The spherically symmetric earth: observational aspects and constraints on new models (abstract), *EOS Trans. AGU*, 69, 1310, 1988.

Woodhouse, J. H., and A. M. Dziewonski, Mapping the upper mantle: three-dimensional modeling of earth structure by inversion of seismic waveforms, *J. Geophys. Res.*, 89, 5953-5986, 1984.

ACKNOWLEDGMENTS

This research was sponsored by DARPA under AFGL contract F19628-87-K-004. L. S. Gee was supported by an Air Force Graduate Fellowship.

POLARIZATION ANISOTROPY AND FINE-SCALE STRUCTURE OF THE EURASIAN UPPER MANTLE

LIND S. GEE AND THOMAS H. JORDAN

Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology

Abstract. We have observed shear-wave splitting, with $(t_{SH}-t_{SV})/t_{SV}$ up to 1.5%, on long-period records of multiply reflected S waves bottoming in the upper mantle beneath the Russian and Siberian platforms. The dispersion of Love and Rayleigh waves over these paths shows discrepancies of comparable or larger magnitude with respect to smooth, isotropic (SI) structures, consistent with a model of the uppermost mantle having significant apparent vertical anisotropy. Although the splitting and dispersion data can be fit by smooth, anisotropic (SA) models, we have investigated the apparent anisotropy associated with fine-scale ("rough") structure beneath stable Eurasia. We fit the data with a rough, isotropic (RI) model having an rms shear velocity fluctuation that varies from 14% in the uppermost mantle to zero at 400-km depth. These fluctuations are larger than the variation in isotropically averaged parameters expected for even a diverse assemblage of upper-mantle ultrabasic rocks, which we take to be evidence for some sort of intrinsic (local) anisotropy.

Introduction

Although seismological studies have begun to illuminate the fine structure of the upper mantle, very little can yet be said to quantify the spatial distribution of wave-speed heterogeneity and anisotropy. A particularly interesting region for the study of small-scale structure is the continental upper mantle, where comparisons between data and the predictions of smooth, isotropic (SI) earth models reveal several discrepancies:

Love-Rayleigh (LR) discrepancy. The problems of satisfying the dispersion of Love and Rayleigh waves by SI structures is well documented (McEvilly, 1964; Cara et al., 1980; L  v  que and Cara, 1983). The discrepancy appears to be global in nature, and some form of radial anisotropy (our preferred term for the type of anisotropy whose contrapositive is transverse isotropy) is usually invoked to explain it (e.g., Anderson and Dziewonski, 1982). The significance of the LR discrepancy for the continents has been debated (James, 1971; Mitchell, 1984).

SNA-EU2 discrepancy. Structures of the upper mantle beneath stable cratons derived from waveform matches to SH -polarized waves, specifically the SNA model of Grand and Helmberger [1984], have consistently higher v_s values in the upper 400 km than structures derived from PSV -polarized waves, specifically the EU2 model of Lerner-Lam and Jordan [1987]. Lerner-Lam and Jordan argue that the SNA-EU2 discrepancy cannot be entirely explained by path differences and must involve polarization anisotropy in the continental upper mantle.

S_n discrepancy. The apparent velocities of high-frequency (~ 1 Hz) S_n waves on both horizontal and vertical components are typically 100–300 m/s higher than the average shear velocity v_s of the uppermost mantle inferred from low-frequency (~ 0.1 Hz) Rayleigh waves. Although not systematically treated in the literature, this problem is evident in the comparison of the S_n velocities of Heustis et al. [1973] with Rayleigh-wave models such as EU2 (Figure 1).

In this paper, we report some new observations of shear-wave splitting for multiple- S waves bottoming beneath Eurasia that are relevant to these discrepancies, and we attempt to explain them in terms of a stochastic model of fine-scale upper mantle structure.

Observations

We have measured the travel times (both phase and group delays) of direct and multiply reflected S waves and

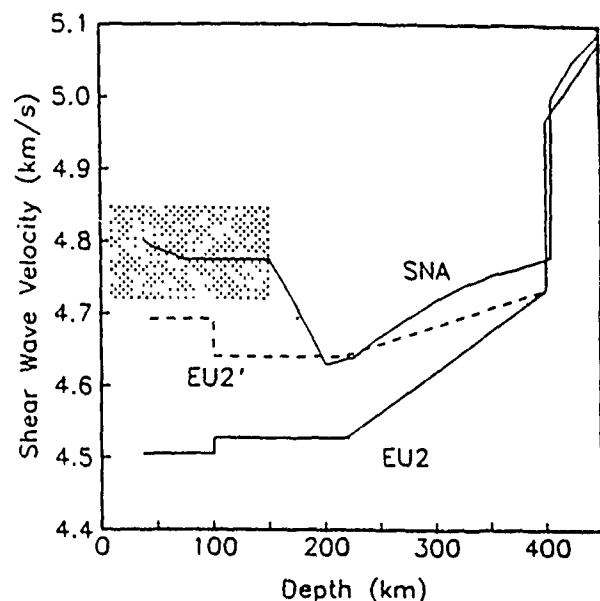


Fig. 1. Shear velocity as a function of depth for continental models EU2 and SNA. Stippling indicates the range of regional S_n velocities typical of continental cratons (Heustis et al., 1973). The dashed line labeled EU2' is the SH velocity structure corresponding to the RI model in Table 1.

fundamental-mode surface waves on 40 three-component records from the Global Digital Seismic Network (GDSN) stations KONO and GRFO for two corridors across Eurasia (Figure 2). The northern Eurasia corridor is nearly identical to that used in deriving EU2; it includes the marginal basins and active foldbelts east of the Verkhoyansk suture, as well as the stable cratons of the Russian and Siberian platforms. The southwestern Eurasia corridor includes two paths, one crossing the central part of the Russian platform from Hindu Kush events to KONO, and one traversing the southwestern margin of the platform along the Alpine-Himalayan front to GRFO. Large variations in SS travel times are observed across the transition from the Russian platform to the Alpine-Himalayan orogenic belt, the latter yielding times delayed by as much as 20–30 s (Rial et al., 1984). Grand and Helmberger [1985] find that SNA satisfies the data from SH body waves propagating across the central Russian platform.

Our technique for measuring travel times is based the ability to synthesize complete seismograms by normal-mode summation [Gee and Jordan, 1986]. A narrow-band isolation filter for a particular wave group, such as a body-wave pulse or a fundamental-mode surface wave, is computed by a convenient method (we use both ray and mode theoretic algorithms) and cross-correlated with both the observed seismogram and the complete normal-mode synthetic for an appropriate source location and mechanism. The difference between the peak times of the observed and synthetic cross-correlation functions is measured and corrected for differential dispersion and attenuation to obtain the differential phase-delay time Δt at the center frequency f_0 of the isolation filter. Δt thus measures the difference between the true arrival time and the model-predicted time at f_0 . This phase-isolation technique provides a self-consistent methodology for measuring the travel times of complex wave groups on three-component seismograms. The complications handled by the technique include caustic phase shifts, interference among multiple arrivals, dispersion, attenuation, and differences in polarization.

Copyright 1988 by the American Geophysical Union.

Paper Number 8L6812.

0094-8276/88/0081-6812\$03.00

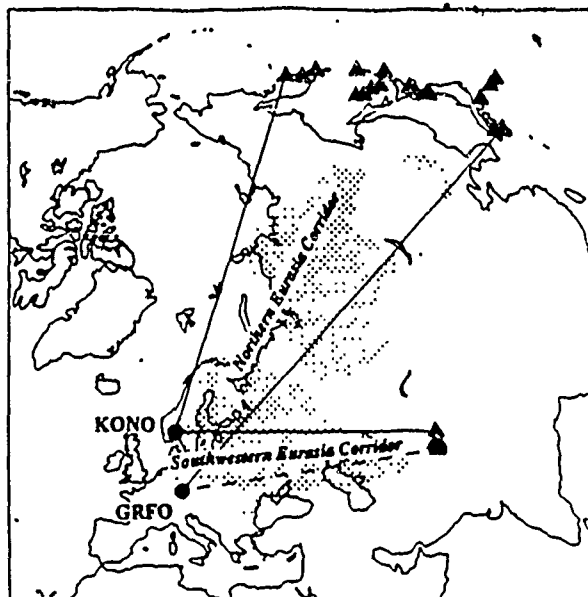


Fig. 2. Azimuthal equidistant projection centered on KONO, illustrating the source-receiver geometry. Triangles are earthquake locations; octagons are receiver locations. Shields and stable platforms (shaded) are from Jordan [1981].

For the body-wave data presented in this paper, the center frequencies of the isolation filters range from 25-30 mHz, and their bandwidths from 8-10 mHz; the standard errors of measurement are typically 1-2 s, excluding the bias due to unmodeled interference. The surface waves were measured in the band $10 \leq f_0 \leq 25$ mHz using isolation filters with bandwidths of $0.15 f_0$, yielding an experimental precision of $\sim 0.1 f_0^{-1}$, or about 5 s for a 20-mHz observation.

Examples of seismograms on which these measurements have been made are presented in Figures 3 and 4. The best match between data and synthetics is obtained by using EU2 as the reference model for computing the isolation filters and complete synthetics for the northern Eurasia corridor and SNA for the southwestern Eurasia corridor (although the results of the data

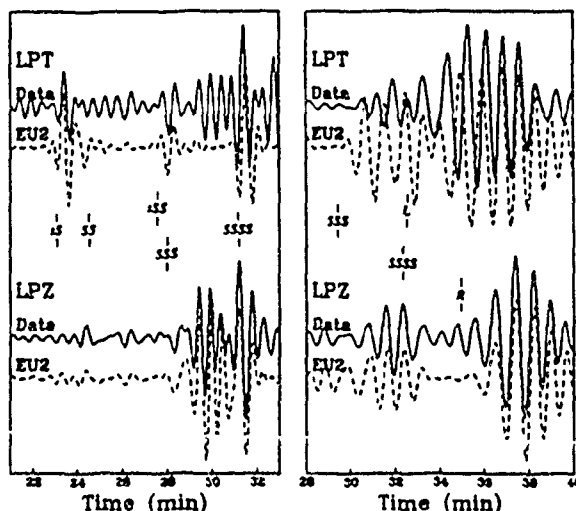


Fig. 3. Comparison of transverse and vertical component seismograms from northern Eurasian paths with EU2 synthetics. (a) Shear-wave splitting in SSSS at GRFO for the 01 Feb 84 Sea of Okhotsk event. Observed seismograms shifted by +2.5 s to align the SSSS pulse on the vertical component; $\Delta\tau_{SSS}$ is 6 s. (b) LR discrepancy at KONO for the 25 Aug 83 Kyushu event. Observed seismograms shifted by +3.2 s to align the Rayleigh wave; $\Delta\tau_{LR}$ is 39 s for $f_0 = 20$ mHz.

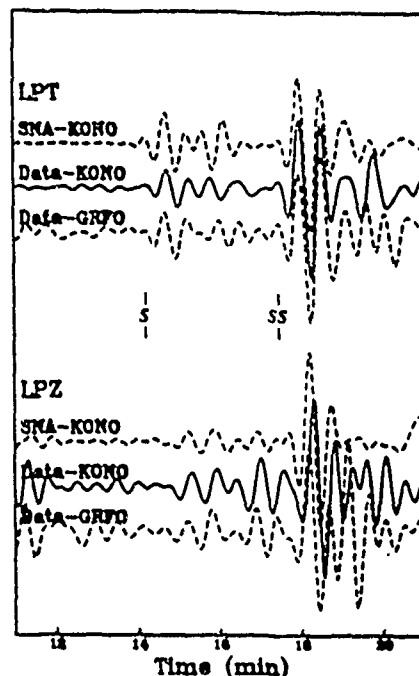


Fig. 4. Example of shear-wave splitting in SS for a path crossing the Russian platform from the 01 Jul 84 Hindu Kush event. The traces for GRFO have been shifted by +2.5 s and the traces for KONO have been shifted by +1.5 s to align the SS pulses with the SNA synthetic on the transverse component. $\Delta\tau_{SS}$ is 5 s for KONO, but less than 1 s for GRFO.

analysis are essentially independent of this choice). EU2 provides a good fit to the Rayleigh waves and PSV-polarized waveforms of multiply reflected S phases for the northern Eurasia corridor, but is too slow for the Love waves and SH-polarized phases with turning points in the upper mantle (Figure 3). SNA is generally consistent with the waveforms and travel times of SH-polarized body phases for paths to KONO across the Russian platform, but is too fast for the PSV-polarized SS phases with turning points in the upper mantle (Figure 4).

On the other hand, the path to GRFO along the southwestern margin of the Russian platform does not show this polarization difference; the observed travel times exceed those predicted by SNA by about 15 s on both components, consistent with the SH observations of Rial et al. [1984]. Shifting the synthetics by this amount aligns the SH and PSV waveforms equally well. Therefore, the data-synthetic comparisons indicate strong shear-wave splitting for the northern Eurasia and central Russian platform paths, but not for paths along the Alpine-Himalayan front.

To quantify the polarization difference in the data-model residual for a specific source-receiver pair, we define an "apparent splitting time" by

$$\Delta\tau = \Delta\tau_{SH} - \Delta\tau_{PSV} \quad (1)$$

where $\Delta\tau_{SH}$ is the phase-delay time measured for a particular wave group on the transverse component and $\Delta\tau_{PSV}$ is the phase-delay time for the corresponding wave group on the vertical component. In the case of body waves, we employ the standard phase notation as a subscript; e.g., $\Delta\tau_{SS}$ is the difference between the travel-time residual for an SS arrival on the transverse component and its residual on the vertical component. For surface waves, however, we choose $\Delta\tau_{SH}$ to be the Love-wave phase delay and $\Delta\tau_{PSV}$ to be the Rayleigh-wave phase delay at the same f_0 and let $\Delta\tau_{LR}$ denote the difference. Hence, the values of $\Delta\tau$ for body waves are essentially independent of the reference model (to the extent that it correctly predicts the interference effects), while the values of $\Delta\tau_{LR}$ depend on the differential dispersion between Love and Rayleigh waves of the reference model.

Figure 5 summarizes the data for northern Eurasia (circles) and the Russian platform (crosses). The apparent splitting time, expressed as a percentage of the total PSV travel time, is plotted

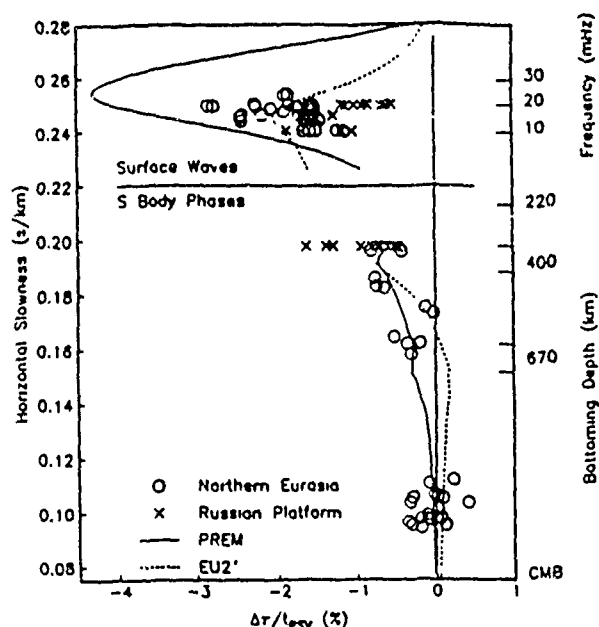


Fig. 5. The ratio $\Delta t/t_{PSV}$ as a function of horizontal slowness for the data and models discussed in this study. Circles are measurements from the northern Eurasia corridor, and crosses from the Russian platform path. The zero line corresponds to the isotropic reference model EU2. Calculated values from PREM, modified to have an EU2 crust, are indicated by solid lines. Short dashed lines labeled EU2' are calculated from the RI model in Table 1. Body-wave travel times for the radially anisotropic models calculated using the algorithm of Cormier [1986].

against the horizontal slowness of the wavegroup computed from the EU2 reference model. The northern Eurasia body wave data include observations of S, SSS, SSSS, and SSSSS between 60° and 90°. The cluster of points with ray parameters between .09 and .12 s/km are S waves that bottom in the lower mantle and do not exhibit any significant splitting. However, the multiply reflected S waves which turn in the upper mantle and transition zone, such as SSS from 65° to 75° and SSSS from 75° to 85°, are split with values of Δt up to 12 s. For the body waves, the largest values of the ratio $\Delta t/t_{PSV}$ are the Russian platform observations of SS in the range 43° to 46°. The LR discrepancy for northern Eurasia, which has a mean value of $-1.8\% \pm .08\%$, is somewhat larger in magnitude than that for the Russian platform ($-1.1\% \pm .09\%$). There is an indication of systematic variations in $\Delta t/t_{PSV}$ with frequency, but the present data set is inadequate to quantify the effect.

As shown in Figure 5, the apparent splitting times for the northern Eurasia and Russian platform paths vary systematically with horizontal slowness: phases most sensitive to velocity perturbations in the uppermost mantle display the greatest apparent splitting. For comparison, we also plot the apparent splitting times computed from two models: (1) Dziewonski and Anderson's [1981] radially anisotropic earth model PREM, modified to have an EU2 crust, and (2) an isotropic, finely layered stochastic model which we now describe.

Interpretation

The body-wave measurements are very consistent with the shear-wave splitting computed from PREM. However, the surface-wave observations show a smaller LR discrepancy than predicted by this radially anisotropic structure. It is certainly possible to derive a smooth, anisotropic (SA) structure that fits the data by relatively small perturbations to the five elastic moduli profiles that characterize PREM. We defer this exercise to a later, more detailed report. However, we find it interesting to note that most aspects of the data can be fit by a rough, isotropic (RI) model whose deviations from an SI structure are given by a single function of depth.

We consider a stochastic model of the upper mantle $m = [\lambda, \mu, \rho]$ in which the variation of isotropic elastic constants and density with vector position $\mathbf{x} = [x_1, x_2, x_3]$ is a small perturbation to a

horizontally layered structure $m(x_3)$, where x_3 is depth. In any particular layer, we write this small perturbation as the product of a constant triplet $(\delta\lambda, \delta\mu, \delta\rho)$ and a homogeneous, scalar-valued, Gaussian random field $f(\mathbf{x})$ with zero mean and autocovariance function

$$C_{ff}(\mathbf{x}) = \langle f(\mathbf{x})f(\mathbf{x}') \rangle = e^{-\sqrt{k_1^2 x_1^2 + k_2^2 x_2^2 + k_3^2 x_3^2}} \quad (2)$$

Such a random field is fractal with Hausdorff dimension 7/2; the two-dimensional version of (2) has proven useful in the study of seafloor morphology, where the parameters $\{k_i\}$ are the characteristic wavenumbers of the abyssal hills [Goff and Jordan, submitted to *J. Geophys. Res.*, 1988].

We assume the characteristic vertical wavenumber is large compared to the two horizontal wavenumbers: $k_1, k_2 \ll k_3$, i.e., the depth variations have much shorter scale lengths than the lateral variations. Then, for waves of length $l \gg k_3^{-1}$, a theoretical argument due to Backus [1962] may be extended to show that the medium responds like a homogeneous, radially anisotropic solid. In the special case where the root-mean-square (rms) perturbations are described by a single, small fluctuation parameter $\epsilon = \delta\mu/\bar{\mu} = \delta\lambda/\bar{\lambda} \ll 1$, Backus's averaging procedure yields to $O(\epsilon^2)$,

$$\begin{aligned} v_{PV}^2 &= \bar{v}_P^2(1 - \epsilon^2), & v_{PH}^2 &= \bar{v}_P^2(1 - \bar{\lambda}^2/\bar{\sigma}^2 \epsilon^2) \\ v_{SV}^2 &= \bar{v}_S^2(1 - \epsilon^2), & v_{SH}^2 &= \bar{v}_S^2 \\ \eta &= 1 - (\bar{\sigma}/\bar{\lambda} - \bar{\lambda}/\bar{\sigma})\epsilon^2 \end{aligned} \quad (3)$$

where $\bar{\sigma} = \bar{\lambda} + 2\bar{\mu}$.

These equations allow us to calculate an SA model $\{v_{PH}, v_{PV}, v_{SH}, v_{SV}, \eta\}$ that is equivalent to the RI model $\{v_P, v_S, \epsilon\}$ in the long-wavelength limit. An example is given in Table 1. In deriving this structure, we took v_{PV} and v_{SV} from EU2 and computed v_{PH} , v_{SH} and η from the values of ϵ listed in the table. We found that the LR discrepancy could be satisfied by an uppermost mantle with $\epsilon = .28$. This yields a long-wavelength SH-SV velocity difference of 4.2% for a ray angle of 90° (horizontal path), which accounts for most of the SNA-EU2 discrepancy (Figure 1). The SH-SV difference described by (3) is a strong function of ray angle, becoming negative for angles steeper than about 52°. Consequently, to explain the magnitude of the shear-wave splitting observed for rays with bottoming depths in the transition zone, it was necessary to maintain a relatively large value of ϵ to depths greater than 200 km. In our example structure, ϵ decreases linearly from .22 at 220 km to zero at 400 km. Given the scatter, the model is consistent with most of the observations, although it predicts a somewhat smaller amount of splitting than is observed for rays bottoming near the 670-km discontinuity for the northern Eurasian paths.

This modeling exercise establishes the magnitude of the velocity heterogeneity needed to explain the splitting data by an RI mechanism. It is large: a value of $\epsilon = .28$ corresponds to a 14% rms fluctuation in the isotropic wave speeds. This exceeds the variation in isotropically averaged parameters expected for even a diverse assemblage of upper-mantle ultrabasic rocks, which we interpret as evidence for intrinsic (local) anisotropy. This interpretation is consistent with investigations of the azimuthal variation in Pn velocity [Fuchs, 1983] and shear-wave splitting in SKS [Silver and Chan, 1988] in Western Europe, which provide additional evidence for intrinsic anisotropy within the continental lithosphere.

In future modeling work, we intend to generalize the Gaussian stochastic description represented by (2) to include the tensor

Table 1. RI and equivalent SA models for Eurasian paths.

Depth (km)	ϵ	v_{PH} (km/s)	v_{PV} (km/s)	v_{SH} (km/s)	v_{SV} (km/s)	η
40-100	.28	8.48	8.19	4.69	4.51	0.85
100-200	.22	8.36	8.19	4.64	4.53	0.90
220	.22	8.32	8.14	4.64	4.53	0.90
400	0	8.65	8.65	4.74	4.74	1.00

All values linearly interpolated between 220 and 400 km.

properties of local anisotropy; i.e., we will consider rough, anisotropic (RA) structures. These structures may be divided into two classes based on the organization of the anisotropy: models where the elasticity tensor averaged over some volume is isotropic, and models which contain a smooth component of anisotropy. Preliminary calculations indicate that the former are inconsistent with petrologic constraints and that a smooth component of anisotropy is required.

In terms of (2) and its generalizations, the qualitative difference between smooth and rough structures is represented as a quantitative difference in the characteristic wavenumbers (k_i). The long-wavelength splitting data presented in this paper do not constrain these wavenumbers. However, the fact that the first arrival times from short-period S_n waves on both horizontal and vertical components yield high apparent velocities is evidence that the characteristic vertical scale of the heterogeneity, k_i^{-1} , lies between the lengths of the long-period and short-period waves, say between 100 km and 10 km. In addition to giving apparent anisotropy at long wavelengths, characteristic scale lengths in this intermediate range provide high-velocity "micropaths" at short wavelengths [cf. Flatté, 1979], which could account for the S_n discrepancy. This hypothesis is consistent with the thinking of Fuchs and Schulz [1976], who have suggested that an RA structure is needed to account for the "shingling" of P arrivals observed on long refraction profiles in Europe.

In conclusion, although RI models of the upper mantle may be constructed which satisfy the splitting data, they are inconsistent with petrologic constraints, and a smooth component of intrinsic anisotropy is indicated. Nevertheless, fine-scale heterogeneity in the elastic parameters is likely to play a role in explaining the LR, S_n , and $SNA-EU2$ discrepancies, as well as other aspects of wave propagation in the continental upper mantle. Our observation that the shear-wave splitting is significantly smaller for paths along the Alpine-Himalayan front than for cratonic paths suggests that the large scale variations in anisotropic properties may be related to continental deep structure.

Acknowledgements. We thank V. Cormier, J. Goff, and an anonymous reviewer for helpful comments. This research was supported by DARPA and AFGL under contract F19628-87-K-0040 and by the MacArthur Foundation through an internal MIT grant. L. Gee was supported by an Air Force Graduate Fellowship.

References

- Anderson, D. L., and A. M. Dziewonski, Upper mantle anisotropy: evidence from free oscillations, *Geophys. J. R. astr. Soc.*, **69**, 383-404, 1982.
- Backus, G. E., Long-wave elastic anisotropy produced by horizontal layering, *J. Geophys. Res.*, **67**, 4427-4440, 1962.
- Dziewonski, A. M., and D. L. Anderson, Preliminary reference earth model, *Phys. Earth Planet. Int.*, **25**, 297-356, 1981.
- Cara, M., A. Nercessian, and G. Nolet, New inferences from higher mode data in western Europe and northern Eurasia, *Geophys. J. R. astr. Soc.*, **61**, 459-478, 1980.
- Cormier, V. F., Synthesis of body waves in transversely isotropic earth models, *Bull. Seis. Soc. Am.*, **76**, 231-240, 1986.
- Flatté, S. M. (ed.), *Sound Transmission through a Fluctuating Ocean*, Cambridge University Press, New York, 299 pp., 1979.
- Fuchs, K., Recently formed elastic anisotropy and petrological models for the continental subcrustal lithosphere in southern Germany, *Phys. Earth Planet. Int.*, **31**, 93-118, 1983.
- Fuchs, K., and K. Schulz, Tunneling of low-frequency waves through the subcrustal lithosphere, *J. Geophys.*, **42**, 175-190, 1976.
- Gee, L. S., and T. H. Jordan, Parameter retrieval using three-component seismograms and hybrid synthetics: an application to seismic anisotropy, *Eos Trans. AGU*, **67**, 1113, 1986.
- Grand, S. P., and D. V. Helmberger, Upper mantle shear structure of North America, *Geophys. J. R. astr. Soc.*, **76**, 399-438, 1984.
- Grand, S. P., and D. V. Helmberger, Upper mantle shear structure beneath Asia from multi-bounce S waves, *Phys. Earth Planet. Int.*, **41**, 154-169, 1985.
- Heustis, S., P. Molnar, and J. Oliver, Regional S_n velocities and shear velocity in the upper mantle, *Bull. Seis. Soc. Am.*, **63**, 469-475, 1973.
- James, D. E., Anomalous Love wave phase velocities, *J. Geophys. Res.*, **76**, 2077-2083, 1971.
- Jordan, T. H., Global tectonic regionalization for seismological data analysis, *Bull. Seis. Soc. Am.*, **71**, 1131-1141, 1981.
- Lerner-Lam, A. L., and T. H. Jordan, How thick are the continents?, *J. Geophys. Res.*, **92**, 14007-14026, 1987.
- Lévesque, J.-J., and M. Cara, Long-period Love wave overtone data in North America and the Pacific Ocean: new evidence for upper mantle anisotropy, *Phys. Earth Planet. Int.*, **33**, 164-179, 1983.
- McEvilly, T. V., Central US crust-upper mantle structure from Love and Rayleigh wave phase velocity inversion, *Bull. Seis. Soc. Am.*, **54**, 1997-2015, 1964.
- Mitchell, B. J., On the inversion of Love and Rayleigh-wave dispersion and implications for earth structure and anisotropy, *Geophys. J. R. astr. Soc.*, **76**, 233-241, 1984.
- Rial, J. A., S. P. Grand, and D. V. Helmberger, A note on lateral variation in upper mantle shear-wave velocity across the Alpine front, *Geophys. J. R. astr. Soc.*, **77**, 639-654, 1984.
- Silver, P. G., and W. Chan, Constraints on early continental evolution from observations of seismic anisotropy, *Eos Trans. AGU*, **69**, 483, 1988.

L. S. Gee and T. H. Jordan, Department of Earth, Atmospheric, and Planetary Sciences, MIT, Cambridge, MA 02139.

(Received April 6, 1988;
Accepted June 2, 1988.)

CONCURRENCE FORM

The Armstrong Aerospace Medical Research Laboratory requests the continuation of the AFOSR fellowship for Ms. Elena Plante, studying Psychophysiology at The University of Arizona.

Give a brief statement of laboratory and/or Mr. Marvis Vikmanis's (fellow's mentor) involvement with Ms. Elena M. Plante.

Ms. Plante spent last summer at our Laboratory working with Dr. Glenn Wilson. Data was collected on sources of 600 Hz tones with the MEG. The language hemisphere of the brain had a larger field. MEG scans of the same subjects were obtained in order to determine if any anatomical differences can be localized also. Ms. Plante has been analyzing the MEG data during this school year and is in regular contact with Glenn Wilson and Capt. Al Badeau. We are collaborating on a journal article in this subject, and she has already drafted an Intro and Methods section.

 16 Apr 89

Chief Scientist Date
DR BILLY WELCH
HQ HSD/CA
Brooks AFB TX 78235-5000



Mentor Date
MARIS M. VIKMANIS
AAMRL/HEG
WPAFB OH 45433-6573

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Ms. Elena M. Plante

University: University of Arizona

Subcontract: S-789-000-006

Fellow to complete

1. Courses - Give description of courses and grades received. (attach sheet if extra space is needed)

See Attached Sheet

2. Give a detailed description of research and progress toward dissertation. (attach sheets if extra space is needed)

See Attached Sheet

"I certify that all information
stated is correct and complete."

Elena Plante
Signature/Fellowship Recipient

ELENA PLANTE
TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Ms. Elena M. Plante is making satisfactory academic
progress toward a Ph.D. in the area of Psychophysiology in the discipline
of Speech and Hearing Sciences for the Spring 1989 semester."

Linda Swisher
Signature/Advising Professor

LINDA SWISHER/Associate Professor
TYPED NAME/TITLE OF ADVISING
PROFESSOR

LLD/sdp 4563C

Progress Certification: Elena Plante
March 27, 1989

1. Coursework from June, 1988 to May, 1989

Course title	credits	grade
Research Design	1	S
Seminar in Language	3	S
Current issues in Speech and Hearing	1	S
Indp. Study: Grant proposal	3	S
Indp. Study: PET scanning	3	S
Statistics	Audit	-
Psychoacoustics	3	NA
Current issues	1	NA
Indp. Study: Electrophysiology	3	NA

S= superior

NA= not available

2. Program of research & activities completed during the accademic year

Lauter, J., & Plante, E. (1989). Global asymmetries in regional cerebral blood flow (rCBF) observed during resting conditions with positron emission tomography (PET): establishing a baseline for experiments on brain asymmetries and complex sounds in the CNS project. Paper accepted for presentation at the Accoustical Society conference, Boston, MA, May.

Plante, E., Swisher, L., & Vance, R. (in press). Anatomical correlates of normal and impaired language in a set of dizygotic twins. Brain & Language.

Plante, E. (1989, April). Neuroanatomical findings in parents and siblings of language impaired children: a dissertation prospectus. Presented to the Department of Speech and Hearing Sciences, The University of Arizona, Tucson, Az.

Plante, E. (1988, December). MRI and language impairment in children. Paper presented to the Arizona chapter of the Society for Neuroscience, Pheonix, AZ.

Plante, E. (1988, November). MRI findings in children with specific language impairment. Paper presented at the Annual convention of the American Speech and Hearing Association, Boston, MA,

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. John Gierke

Semester: Spring 1989

University: Michigan Technology

Subcontract: S-789-000-007

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

CE 600 - Research Grade: P - Progress

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Completed manuscript and submitted to Water Resources Research for review in March 1989 (see attached sheet). Began two-dimensional model development. Designed experiments to verify the one-dimensional models.

3. Give brief statement of your involvement with the Engineering and Services Center Laboratory and Dr. Cornette.

I have not required assistance from the Engineering Services Center Laboratory to date. My mentor at this time is Tom Stauffer so I have not been in contact with Dr. Cornette.

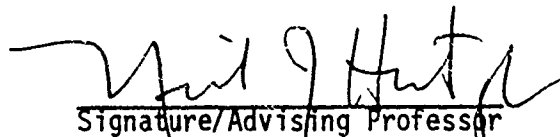
"I certify that all information stated is correct and complete."


Signature/Fellowship Recipient

John S. Gierke
TYPED NAME/FELLOWSHIP RECIPIENT

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. John Gierke is making satisfactory academic progress toward a Ph.D. in the area of Environmental Chemistry in the discipline of Civil Engineering for the Summer 1989 semester."


Signature/Advising Professor

~~Dr. Neil I. Hutzler, P.E., Associate Professor of Civil and Environmental Engineering~~
TYPED NAME/TITLE OF ADVISING
PROFESSOR

2094t

PROGRESS OF JOHN S. GIERKE DURING THE SPRING OF 1989

PAPER SUBMITTED FOR REVIEW:

Gierke, J.S., N.J. Hutzler, and J.C. Crittenden, "Modeling the Movement of Volatile Organic Chemicals in Columns of Unsaturated Soil," submitted for review for publication in Water Resources Research, 1989.

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. John Gierke

Semester: Summer 1989

University: Michigan Technology

Subcontract: S-789-000-007

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

CE 600 - Doctoral Research (3 credits) Grade: P - Progress

2. Give a description of research and progress toward dissertation.

(Attach sheets if extra space is needed.)

Coauthor for two oral papers (see attached sheet). Attended the IAWPRC Symposium at Stanford, July 24-26. Continued development of two-dimensional models. Began preparation on PhD dissertation; I expect to complete the requirements for a PhD degree by March 1990.

3. Give brief statement of your involvement with the Engineering and Services Center Laboratory and Dr. Cornette.

I had no contact with ESCL during the summer of 1989.

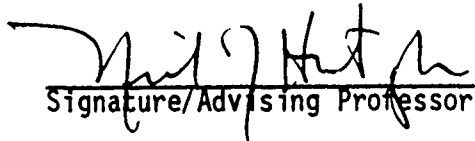
"I certify that all information stated is correct and complete."


Signature/Fellowship Recipient

John S. Gierke
TYPED NAME/FELLOWSHIP RECIPIENT

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. John Gierke is making satisfactory academic progress toward a Ph.D. in the area of Environmental Chemistry in the discipline of Civil Engineering for the Spring 1989 semester."


Signature/Advising Professor

Dr. Neil J. Hutzler, P.E., Associate Professor of Civil and Environmental Engineer
TYPED NAME/TITLE OF ADVISING
PROFESSOR

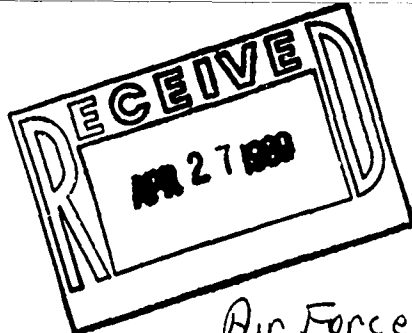
2094t

PROGRESS OF JOHN S. GIERKE DURING THE SUMMER OF 1989

ORAL PRESENTATIONS:

"Review of Soil Vapor Extraction System Technology," with N.J. Hutzler and B.E. Murphy, Soil Vapor Extraction Technology for Underground Storage Tank Sites Workshop, USEPA Risk Reduction Engineering Laboratory, Edison, New Jersey, June 27-28, 1989.

"Vapor Extraction of Volatile Organic Chemicals from Unsaturated Soil," with N.J. Hutzler and D.B. McKenzie, International Symposium on Processes Governing the Movement and Fate of Contaminants in the Subsurface Environment, International Association on Water Pollution Research and Control, Stanford, California, July 24-26, 1989.



CONCURRENCE FORM

Air Force Engineering and Services Center

The ~~Engineering Science Center~~ requests the continuation of the AFOSR fellowship for Mr. John S. Gierke, studying Environmental Chemistry at Michigan Technological University.

Give a brief statement of laboratory and/or Dr. Jimmy Cornette's (fellow's mentor) involvement with Mr. John S. Gierke.

Interaction with Mr Gierke is continuing by phone. He has visited the Center once for a seminar and he keeps us posted on his progress.

Daniel R. Stone 21 Apr 89

Chief Scientist

Date

Jimmy Cornette 20 Apr 89

Mentor

Date

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. John S. Gierke

University: Michigan Technological University Subcontract: S-789-000-007

Fellow to complete

1. Courses - Give description of courses and grades received. (attach sheet if extra space is needed)

CE 600 - Graduate Research 3 credits Grade: P (Progress)

2. Give a detailed description of research and progress toward dissertation. (attach sheets if extra space is needed)


During the fall I helped write a Research Initiation Proposal entitled, "Soil Vapor Extraction of Volatile Organic Chemicals." The principal investigator, Neil Hutzler, submitted this to your office on 6 October 1988 and subsequently awarded funding. I also worked on a oral presentation (abstract enclosed) and submitted an abstract for an oral presentation to be given this summer (abstract attached). In addition, I have been writing a paper and continuing my model development.

I certify that all information stated is correct and complete."


Signature/Fellowship Recipient

John S. Gierke
TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mr. John S. Gierke is making satisfactory academic progress toward a Ph.D. in the area of Environmental Chemistry in the discipline of Engineering for the Fall 1988 quarter."


Signature/Advising Professor

Neil J. Hutzler, Ph.D., P.E.
TYPED NAME/TITLE OF ADVISING
PROFESSOR

LLD/sdp 4563C

PRESENTED AT AIGU FALL ¹⁹⁸⁸ MEETING IN SAN

Modeling the Removal of Organic Vapors From Laboratory Columns of Unsaturated Soil

N J Hutzler (Department of Civil Engineering, Michigan Technological University, Houghton, MI 49931; 906-487-2194)

D B McKenzie and J S Gierke (Both at same address as above)

(Sponsor: A G U Member)

A mathematical model was developed, and laboratory experiments were conducted to assess the importance of various transport mechanisms and system variables on the rate of removal of volatile organic chemicals (VOCs) from unsaturated porous materials by vapor extraction. A Dispersed Air Flow, Diffusion in Aggregates Model (DAFDAM) was developed to simulate one-dimensional transport of VOCs in laboratory columns of unsaturated soil. The DAFDAM assumes that removal rates are controlled by gas advection and dispersion, pore diffusion in immobile water, mass transfer resistance at the air/water interface, and sorption onto soil. System variables under study included: moisture content, soil structure, Henry's constant (H), and air flow rate. Columns were packed with uniform sand or a fired, porous clay and contaminated with water containing trichloroethene (TCE), toluene, or 1,1,1-trichloroethane (TCA). Organic-free air was drawn through the column, and exit vapor concentrations were monitored with time. In each experiment the contaminant was rapidly removed from the column by vapor extraction. TCE and toluene exhibited similar behavior in the sand because their Henry's constants are approximately the same. TCA, which has a higher H, was removed at a faster rate. Toluene and TCA were more slowly removed from the porous clay because of the time required for liquid diffusion out of the particles. The rates of vapor extraction observed during the experiments were compared to DAFDAM predictions. Excellent agreement exists between model predictions and initial removal rates, however, the model was less successful in simulating the latter part of the removal curve.

1. 1988 Fall Meeting
2. 005460604
3. (a) N J Hutzler
Department of Civil Engineering
Michigan Technological Univ.
Houghton, MI 49931

(b) 906-487-2194
4. H
5. (a) H16 Unsaturated Zone Gases
Transport and Chemistry
(b) 1872 Transport
1866 Soil Moisture
- 6.
7. 10% at ASCE/CSCE 1988 Meeting in
Vancouver, British Columbia
8. Invoice \$40 to PO# 39436
- attached
at Accounting Department
Michigan Technological Univ.
Houghton, MI 49931
9. C
10. None

Abstract for Oral Presentation
at the
International Symposium on Processes Governing the Movement
and Fate of Contaminants in the Subsurface Environment
Stanford University, Stanford, California, U.S.A., July 24-26, 1988

VAPOR EXTRACTION OF VOLATILE ORGANIC CHEMICALS FROM UNSATURATED SOIL

Neil J. Hutzler, David B. McKenzie, and John S. Gierke
Department of Civil Engineering, Michigan Technological University, Houghton

Vapor extraction is an accepted technology for removing volatile organic chemicals (VOCs) from the unsaturated zone above ground water aquifers. A vapor extraction system (VES) removes VOCs from the vadose zone by inducing air flow through the soil which results in volatilization of the contaminants. The vapors are withdrawn from extraction wells by a vacuum applied with blowers. Clean air is drawn or injected into the soil through air inlet wells. Presently, the design of soil vapor extraction systems is based on operational experience and trial and error rather than theoretical calculations. The current level of understanding recommends that air withdrawal rates are as fast as possible, however, consideration must also be given for the time required for equilibrium to be established between the air, water, organic, and soil phases.

This study has measured the relative impacts of vapor diffusion, air-water mass transfer, and pore diffusion on the removal of VOCs from unsaturated soils. A combination of soil column experiments and model calculations has been used to quantify the effects of these mechanisms as a function of air withdrawal rate, pumping duration, chemical partitioning, and soil structure.

A set of models is used to describe the one-dimensional transport of VOC vapors in laboratory soil columns. The mechanisms and reactions that are considered include: (a) air advection, (b) vapor diffusion, (c) air-water mass transfer, (d) diffusion in immobile water, (e) sorption, and (f) Henry's partitioning. Deterministic models are developed for various simplifying conditions. The models are solved analytically when possible; numerical methods are used for the more general cases. Model calculations are used to interpret the experimental results and assess the relative importance of the various mechanisms. In addition, model predictions are compared to laboratory data to determine the validity of the models.

Laboratory experiments are used to simulate simplified field systems under controlled conditions. Soil columns packed with cohesionless and structured soil materials are used in the column experiments to compare the effects of chemical diffusion in immobile water on the rate at which VOCs are removed by vapor extraction. Properties of some of the soil materials used in this study are listed in Table 1. Ottawa sand is used to simulate a cohesionless soil. Verilite is a fired clay and is used to simulate an aggregated soil. The primary difference between the sand and clay is that the clay particles contain an internal porosity while the sand particles are solid. Therefore, VOCs must diffuse out of the clay particles, which are saturated with water, before being removed with the air flow.

was halted for 23 hours. When pumping resumed the exit concentration increased because the flow stoppage had allowed time for toluene to diffuse out of the particles. Moreover, the rate of concentration reduction increased after restarting the air flow. The impact of pulsing is greater when the air flow is stopped sooner.

Table 2. Conditions of laboratory experiments shown in Figure 1.

Soil:	<u>Ottawa Sand</u>		<u>Verilite</u>	
Chemical:	<u>Toluene</u>	<u>TCA</u>	<u>Toluene</u>	<u>TCA</u>
Conditions				
Air Flow Rate (mL/min):	4.0	3.0	3.1	3.0
Temperature (°C):	24	22	21	22
Pressure (mm Hg):	768	764	764	764
Vapor Concentration (mg/L):	15.2	11.5	17.5	12.5
Column Length (cm):	29.9	29.9	20.1	20.1
Column Diameter (cm):	10.8	10.8	10.8	10.8
Length of Run (hrs):	69	47	160	93

Figure 2 is an example of a model prediction. The model assumes steady, continuous flow through a homogeneous, aggregated soil. The model did not predict the total mass of chemical removed from the column. This may be due to vapor sorption or the estimate of Henry's constant is too high. Model predictions of the four experiments were similar to the one shown in Figure 2. The model predicts that air advection and diffusion as well as diffusion in immobile water are significant mass transfer mechanisms under the conditions shown in Figure 2 and that air-water mass transfer is fast. Model calculations indicate that only air advection and diffusion are important for removal from the sand.

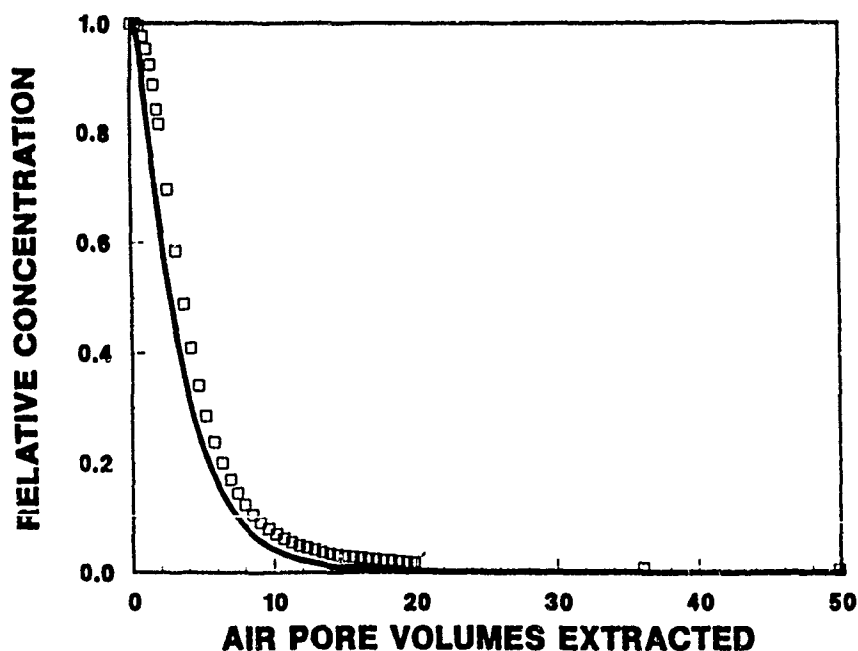


Figure 2. Model prediction of TCA removal from Verilite.

was halted for 23 hours. When pumping resumed the exit concentration increased because the flow stoppage had allowed time for toluene to diffuse out of the particles. Moreover, the rate of concentration reduction increased after restarting the air flow. The impact of pulsing is greater when the air flow is stopped sooner.

Table 2. Conditions of laboratory experiments shown in Figure 1.

Soil:	<u>Ottawa Sand</u>		<u>Verilite</u>	
	<u>Toluene</u>	<u>TCA</u>	<u>Toluene</u>	<u>TCA</u>
<u>Conditions</u>				
Air Flow Rate (mL/min):	4.0	3.0	3.1	3.0
Temperature (°C):	24	22	21	22
Pressure (mm Hg):	768	764	764	764
Vapor Concentration (mg/L):	15.2	11.5	17.5	12.5
Column Length (cm):	29.9	29.9	20.1	20.1
Column Diameter (cm):	10.8	10.8	10.8	10.8
Length of Run (hrs):	69	47	160	93

Figure 2 is an example of a model prediction. The model assumes steady, continuous flow through a homogeneous, aggregated soil. The model did not predict the total mass of chemical removed from the column. This may be due to vapor sorption or the estimate of Henry's constant is too high. Model predictions of the four experiments were similar to the one shown in Figure 2. The model predicts that air advection and diffusion as well as diffusion in immobile water are significant mass transfer mechanisms under the conditions shown in Figure 2 and that air-water mass transfer is fast. Model calculations indicate that only air advection and diffusion are important for removal from the sand.

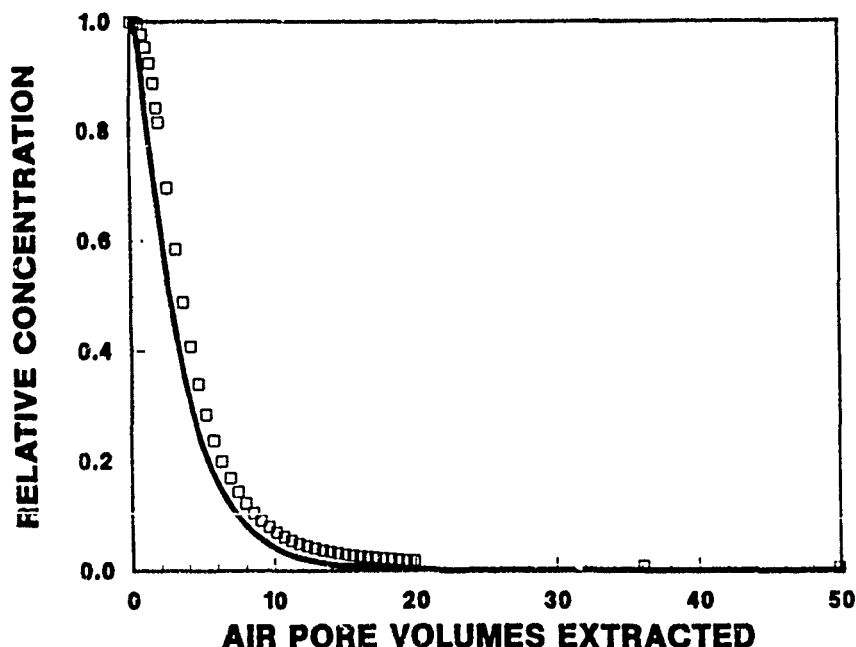


Figure 2. Model prediction of TCA removal from Verilite.

Date: 3/27/89

Dear Sir:

In the latter part of January I submitted the forms and materials for the graduate fellowship program that you are offering. I have not heard anything from the people that are in charge of this project. I was under the impression that they were to have made their decision by March 15, 1989. If this is in error, then I would like to know when they are to make the decision. If I was correct in the decision date, I would like to know what the decision was with regard to my application since award of the fellowship will change my current plans. I have been accepted to the University of Virginia and West Virginia University and am currently planning to enroll for this summer semester if I am unfortunate in not receiving the fellowship award.

As stated in my application materials, I have a very strong desire to work in the exact areas that this fellowship will allow me to work in the summer months. Therefore, I would prefer to work in my fellowship position instead of going on to graduate school this summer.

Sincerely:



Edwin Farrar
1300 Sandpiper #23
Weatherford, OK. 73096

Michigan Technological University



Houghton, Michigan 49931

Department of Civil and Environmental Engineering
Telephone: 906/487-2520
Facsimile: 906/487-2943

March 23, 1989

Ms. Judy Conover
Assistant Program Manager
Laboratory Graduate Fellowship
Universal Energy Systems, Inc.
4401 Dayton-Xenia Rd.
Dayton, Ohio 45432-1894

Dear Ms. Conover:

I am submitting a "Certification of Academic Progress" per the request for a "Statement of Progress" sent by your office on 17 March 1989. I hope they are the same forms. If this is not the correct form, please send me a copy of the correct one.

I must admit that I am confused as to when to send such forms. Should they be sent at the end of each term or only upon request from your office?

I am sorry for the delay.

Sincerely,

A handwritten signature in dark ink, appearing to read 'John S. Glerke'.

John S. Glerke
Laboratory Graduate Fellow

Handwritten notes:
Judy Conover
March 23, 1989
+ [unclear]
[unclear]
[unclear]

CONCURRENCE FORM

The Human Research Laboratory requests the continuation of the AFOSR fellowship for Mr. Kenneth R. Koedinger, studying Skill Acquisition and Intelligence Tutors at Carnegie-Mellon University.

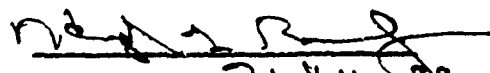
Give a brief statement of laboratory and/or Dr. Thomas B. Stauffer's (fellow's mentor) involvement with Mr. Kenneth R. Koedinger.

Due to Mr Koedinger's course load to date, we have had limited interaction. We look forward to greater interaction with Mr Koedinger and encourage him to spend 10 weeks in our laboratory to facilitate the transition of his technology to our ongoing research and development of intelligent systems.

 174C89

Chief Scientist

Date


31 Jan 89

Mentor

Date

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Kenneth R. Koedinger

Semester: Spring 1989

University: Carnegie-Mellon University

Subcontract: S-789-000-008

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

See section IIA on the enclosed
"Graduate Student Evaluation" form.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

See sections IB+C on the enclosed
"Graduate Student Evaluation" form

"I certify that all information stated is correct and complete."


Ken Koedinger
Signature/Fellowship Recipient

KEN KOEDINGER
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4955C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Kenneth R. Koedinger is making satisfactory academic progress toward a Ph.D. in the area of Skill Acquisition and Intelligence Tutors in the discipline of Psychology for the Spring 1989 semester."



Signature/Advising Professor

JOHN R. ANDERSON
TYPED NAME/TITLE OF ADVISING
PROFESSOR

4955C

Carnegie-Mellon University
Department of Psychology
Graduate Student Evaluation

Name: Ken Koedinger

Date: 6-13-89

Major Area: Cognitive

Advisory Committee Chair: John Anderson

Committee Members: David Klahr, Herb Simon

Other Interested Faculty: Kurt Van Lehn, Jill Larkin

I. Research

A. List, in reverse chronological order, complete citations of all papers and presentations, including major course projects. Describe the state of completion of each (draft, finished manuscript, submitted, in press).

1. CONFERENCE PAPER: "Perceptual Chunks in Geometry Problem Solving: A Challenge to Theories of Skill Acquisition" by K. Koedinger and John R. Anderson. Accepted to the *Eleventh Annual Conference of the Cognitive Science Society*, 1989.
2. ACCEPTED PENDING REVISION: "Abstract Planning and Perceptual Chunks: Elements of Expertise in Geometry" by K. Koedinger and John R. Anderson. Accepted to *Cognitive Science* pending revision, March, 1989.
3. CONFERENCE PAPER: "An Improved Ideal Student Model for Geometry Proof Problem Solving" by K. Koedinger. Presented at the American Educational Research Association conference, March, 1989.
4. 2ND YEAR PAPER: "Using the Concrete to Plan in the Abstract" by K. Koedinger, May 25, 1988.
5. COURSE PROJECT: "Uncovering Content Knowledge in an Ill-Structured Domain: The Organization of Evaluation Knowledge in Typographic Design" for Research Methods, December, 1987.
6. COURSE PROJECT: "Chronometric Evidence for Abstract Planning in Geometry" for Research Methods, November 2, 1987.
7. CONFERENCE TALK: "Abstract Planning and Successive Refinement by Geometry Experts". Presented at the Pitt-CMU Graduate Student Conference on Cognition, June 26, 1987.
8. 1ST YEAR BROWN BAG: "Learning and Transfer of Geometry Strategy" by K. Koedinger, March 13, 1987.
9. COURSE PROJECT: "One More for the 2-4-6 Task" by K. Koedinger for Dr.

Klahr's Scientific Reasoning Seminar, May, 1987.

10. CONFERENCE TALK: "Intelligent Tutoring Systems Design Issues for a Genetics Laboratory Microworld Called MENDEL" by K. Koedinger, R. Maclin, M. J. Streibel and J. Stewart. The Third International Conference on Artificial Intelligence and Education, May 8, 1987.
11. COURSE PROJECT: "A Reinterpretation of the Influences of Affect on Problem Solving and Decision Making" by K. Koedinger for the Social Core, March 31, 1987.
12. COURSE PROJECT: "Identification of Broad Methods in Geometry Proof Experts" by K. Koedinger. Course project for Cognitive Processes and Problem Solving, December, 1986.
13. PUBLICATION: "MENDEL: An Intelligent Tutoring System for Genetics Problem Solving, Conjecturing, and Understanding" by M. J. Streibel, J. Stewart, K. Koedinger, A. Collins, J.R. Junck in Machine-Mediated Learning. Vol. 2, No. 1 & 2, 1987.
14. B.S. THESIS: "Teaching/Learning Mathematical Problem Solving: Lessons from Artificial Intelligence Research" by K. Koedinger. Senior Honors Thesis, 1984.

B. Briefly describe your ongoing research and its state of progress.

This semester I've been involved with research related to DC, a model of geometry expertise, which John Anderson and I have reported on in a paper accepted to the Cognitive Science journal pending revision [2]. I presented a related paper at the AERA conference [3] in March which emphasized the educational implications of DC. We also had a paper accepted to the Cognitive Science conference which presents DC as a challenge to current theories of skill acquisition in that it is not clear how the nature of expertise captured by DC can be achieved within current theories of skill acquisition.

In addition to paper writing, a major task of this semester has been programming an interface which allows users to draw geometry diagrams and mark them in the standard way to indicate geometric relationships therein. This interface is planned for a perception experiment in geometry analogous to the chess board perception studies done by Chase and Simon. In addition, this interface will serve as part of a new geometry tutor we are building based on the DC model.

C. Briefly describe your plans for future research.

This summer I will be involved with designing this new geometry tutor. John Anderson and I have hired a programmer and so I will have time to work on other things. The first task is to revise the Cognitive Science journal paper. The next task is to write a thesis proposal. My plan for a thesis has been to do some or all of the following: 1) collect some data on geometry novice problem solving and learning, 2) develop a learning theory that is consistent with this data and the DC model of geometry expertise, and 3) test the theory, as well as the tutor we are building, in the context of a

tutoring study. However, recently I have been considering an alternative which grows out of John Anderson's new book on rational analysis and the PDP course I took this past semester. In general, I've become quite interested in the knowledge acquisition component of skill acquisition in contrast to the knowledge tuning component which has received much more attention, for example, in ACT* and Soar. John's new book presents a rational analysis of the knowledge acquisition processes of memory, categorization, and causal inference and I am considering taking up the problem of finding a mechanism which satisfies the constraints of one or more of these rational analyses. In the PDP course, I began to explore whether a network architecture like PDP could meet these constraints and if it could be extended or modified to do so. I plan to meet with my advisor and talk with other faculty about the feasibility of pursuing this second alternative.

II. Courses

A. List the title, number, instructor(s), grade, and semester completed. Group items as one or more of the following: depth, breadth, or skill. (Skills can include things such as statistics, writing, or programming).

<u>Course</u>	<u>Number</u>	<u>Instructor(s)</u>	<u>Grade</u>	<u>Semester Completed</u>	<u>Type</u>
Cognitive Core	85-861	Cognitive faculty	A	Fall, 1986	Breadth
Cognitive Processes and Problem Solving	85-711	Van Lehn and Simon	A	Fall, 1986	Depth
Social Core	85-741	Social faculty	B	Spring, 87	Breadth
Advanced Seminar in Developmental Pysch (Scientific Reason.)	85-724	Klahr	A	Spring, 87	Depth
Research Methods	85-773	Carpenter	B	Fall, 87	Skill
Developmental Core	85-721	Developmental fac.	A	Fall, 87	Breadth
Thinking	85-712	Anderson	A	Spring, 88	Depth
PDP	85-719	McClelland	I	Spring, 89	Depth

B. List your current courses and plans for future courses.

I have no further plans for taking courses, except any interesting seminars which may come up.

III. Teaching

A. Briefly describe your experience to date. List the course title, your role in the course, number of students, supervisor, and the semester in which you taught.

<u>Course</u>	<u>Role</u>	<u>No. of students</u>	<u>Semester</u>	<u>Supervisor</u>
Self-Paced LISP	Instructor/admin	~12	Summer II, 87	Anderson

Info Processing TA
Psych and AI

~70 Fall, 87

Anderson

I've had a years experience at the University of Wisconsin as the sole instructor for an introductory programming course.

B. Describe your plans for future teaching. List the course and semester in which you want to teach.

None.

IV. Other

A. List anything else that is relevant to your evaluation, for example: exams, awards, consulting, committee work, conferences or seminars attended, departmental activities.

Air Force-Laboratory Graduate Fellowship.

CMU organizer for the 1988 CMU-Pitt Graduate Student Conference on Cognition.

CONCURRENCE FORM

The Human Research Laboratory requests the continuation of the AFOSR fellowship for Mr. Kenneth R. Koedinger, studying Skill Acquisition and Intelligence Tutors at Carnegie-Mellon University.

Give a brief statement of laboratory and/or Dr. Thomas B. Stauffer's (fellow's mentor) involvement with Mr. Kenneth R. Koedinger.

note: fellow's mentor is Lt Col Hugh Burns, PhD

Direct involvement with Mr. Koedinger has been minimal to date. We are hoping Mr. Koedinger will agree to visit the lab this summer.

Andrew Reed (Mar 89)

Chief Scientist

Date

S.E. Welch, PhD
10 Mar 89

Hugh Burns 3-6-89

Mentor

Date

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Kenneth R. Koedinger

Semester: Fall 1988

University: Carnegie-Mellon University

Subcontract: S-789-000-008

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

I focussed on research this semester and took no courses. The enclosed "Graduate Student Evaluation" contains course information from previous semesters (section II.).

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

See section I on attached "Graduate Student Evaluation".

"I certify that all information stated is correct and complete."

Ken Koedinger
Signature/Fellowship Recipient

Ken Koedinger
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4955C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Kenneth R. Koedinger is making satisfactory academic progress toward a Ph.D. in the area of Skill Acquisition and Intelligence Tutors in the discipline of Psychology for the Fall 1988 semester."



Signature/Advising Professor

John Anderson

TYPED NAME/TITLE OF ADVISING
PROFESSOR

4955C

Carnegie-Mellon University
Department of Psychology
Graduate Student Evaluation

Name: Ken Koedinger

Date: 1-26-89

Major Area: Cognitive

Advisory Committee Chair: John Anderson

Committee Members: David Klahr, Herb Simon

Other Interested Faculty: Kurt Van Lehn, Jill Larkin

I. Research

A. List, in reverse chronological order, complete citations of all papers and presentations, including major course projects. Describe the state of completion of each (draft, finished manuscript, submitted, in press).

1. SUBMITTED FOR PUBLICATION: "Abstract Planning and Perceptual Chunks: Elements of Expertise in Geometry" by K. Koedinger and John R. Anderson. Submitted to the Cognitive Science journal November, 1988.
2. CONFERENCE PAPER: "An Improved Ideal Student Model for Geometry Proof Problem Solving" by K. Koedinger. Accepted for the American Educational Research Association conference, 1989. To be presented March 30, 1989.
3. 2ND YEAR PAPER: "Using the Concrete to Plan in the Abstract" by K. Koedinger, May 25, 1988.
4. COURSE PROJECT: "Uncovering Content Knowledge in an Ill-Structured Domain: The Organization of Evaluation Knowledge in Typographic Design" for Research Methods, December, 1987.
5. COURSE PROJECT: "Chronometric Evidence for Abstract Planning in Geometry" for Research Methods, November 2, 1987.
6. CONFERENCE TALK: "Abstract Planning and Successive Refinement by Geometry Experts". Presented at the Pitt-CMU Graduate Student Conference on Cognition, June 26, 1987.
7. 1ST YEAR BROWN BAG: "Learning and Transfer of Geometry Strategy" by K. Koedinger, March 13, 1987.
8. COURSE PROJECT: "One More for the 2-4-6 Task" by K. Koedinger for Dr. Klahr's Scientific Reasoning Seminar, May, 1987.
9. CONFERENCE TALK: "Intelligent Tutoring Systems Design Issues for a Genetics Laboratory Microworld Called MENDEL" by K. Koedinger, R. MacIin, M. J.

Streibel and J. Stewart. The Third International Conference on Artificial Intelligence and Education, May 8, 1987.

10. COURSE PROJECT: "A Reinterpretation of the Influences of Affect on Problem Solving and Decision Making" by K. Koedinger for the Social Core, March 31, 1987.
11. COURSE PROJECT: "Identification of Broad Methods in Geometry Proof Experts" by K. Koedinger. Course project for Cognitive Processes and Problem Solving, December, 1986.
12. PUBLICATION: "MENDEL: An Intelligent Tutoring System for Genetics Problem Solving, Conjecturing, and Understanding" by M. J. Streibel, J. Stewart, K. Koedinger, A. Collins, J.R. Junck in Machine-Mediated Learning. Vol. 2, No. 1 & 2, 1987.
13. B.S. THESIS: "Teaching/Learning Mathematical Problem Solving: Lessons from Artificial Intelligence Research" by K. Koedinger. Senior Honors Thesis, 1984.

B. Briefly describe your ongoing research and its state of progress.

Over the summer I implemented "DC", a model of geometry proof planning. Although there have been many models of geometry proof planning, DC is unique in its ability to abstract plan, that is, to skip less important proof steps to focus on the more important ones. This abstract planning ability was observed of geometry experts who gave verbal reports while solving proof problems in the studies reported in [11], [3] and [1] above. A theoretical assertion underlying DC is that expert's ability to perform such abstract planning is based on perceptual knowledge or chunks of prototypical parts of geometry diagrams. The theory is that experts have learned that particular configurations of points and lines in geometry diagrams are correlated with particular (and often large) sets of geometric knowledge. By parsing geometry diagrams in terms of these prototypical configurations, experts can drastically reduce the potential search for a problem solution. This fall John Anderson and I wrote a paper on the DC model which was submitted to the journal Cognitive Science.

To follow up of this work, we are currently planning an expert-novice study in which we will collect protocols from both experts (primarily geometry teachers) and novices (both pre- and post-geometry students). In addition, we will also attempt to get further evidence for the perceptual chunks proposed in the DC model by performing a problem state perception experiment analogous to the chess board perception experiments of De Groot and Chase & Simon. I am currently building a computer interface that subjects will use to replicate geometry diagrams that they will view for short periods of time.

C. Briefly describe your plans for future research.

The expert-novice study will be the main research focus of this semester. I plan to have a thesis proposal ready by the end of the semester. I envision my thesis topic to be an extension of the basic ideas developed in the DC model. I'd like to explore the aspects of expert knowledge which go beyond formal (textbook) knowledge of the domain,

some things referred to as "tacit knowledge" or "intuition". I think the idea that expert intuition is just more knowledge (i.e., of the same basic form) may be fundamentally correct but is not very informative. I'd like to put some flesh on the bones of this idea by proposing (and testing) the idea that much of what we think of as expert intuition is actually perceptual knowledge.

In addition to the problem state perception experiment planned for this semester, I have also begun to plan the curriculum and interface for a new geometry tutor based on the DC model. Such a tutor would stand as a test of the DC model and more generally of the idea that acquiring perceptual chunks for a task domain is as important as acquiring the formal knowledge of the domain.

II. Courses

A. List the title, number, instructor(s), grade, and semester completed. Group items as one or more of the following: depth, breadth, or skill. (Skills can include things such as statistics, writing, or programming).

<u>Course</u>	<u>Number</u>	<u>Instructor(s)</u>	<u>Grade</u>	<u>Semester Completed</u>	<u>Type</u>
Cognitive Core	85-861	Cognitive faculty	A	Fall, 1986	Breadth
Cognitive Processes and Problem Solving	85-711	Van Lehn and Simon	A	Fall, 1986	Depth
Social Core	85-741	Social faculty	B	Spring, 87	Breadth
Advanced Seminar in Developmental Psych (Scientific Reason.)	85-724	Klahr	A	Spring, 87	Depth
Research Methods	85-773	Carpenter	B	Fall, 87	Skill
Developmental Core	85-721	Developmental fac.	A	Fall, 87	Breadth
Thinking	85-712	Anderson	A	Spring, 88	Depth

B. List your current courses and plans for future courses.

This spring I am taking the PDP course. I have no further plans for taking courses, except any interesting seminars which may come up.

III. Teaching

A. Briefly describe your experience to date. List the course title, your role in the course, number of students, supervisor, and the semester in which you taught.

<u>Course</u>	<u>Role</u>	<u>No. of students</u>	<u>Semester</u>	<u>Supervisor</u>
Self-Paced LISP	Instructor/admin	~12	Summer II, 87	Anderson
Info Processing	TA	~70	Fall, 87	Anderson
Psych and AI				

I've had a years experience at the University of Wisconsin as the sole instructor for an introductory programming course.

B. Describe your plans for future teaching. List the course and semester in which you want to teach.

None.

IV. Other

A. List anything else that is relevant to your evaluation, for example: exams, awards, consulting, committee work, conferences or seminars attended, departmental activities.

Air Force-Laboratory Graduate Fellowship.

CMU organizer for the 1988 CMU-Pitt Graduate Student Conference on Cognition.

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. David A. Wagner

University: Stanford University

Subcontract: S-789-000-009

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Please see Attachment A Part 1

2. Give a detailed description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Please see Attachment A Part 2

"I certify that all information
stated is correct and complete."

David A. Wagner 7 SEPT 89
Signature/Fellowship Recipient

David A. Wagner
TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mr. David A. Wagner is making satisfactory academic progress toward a Ph.D. in the area of Damage Tolerance Characteristics of Advanced Structural Materials in the discipline of Applied Mechanics for the Spring 1989 quarter."

Sheri D. Sheppard 9-7-89
Signature/Advising Professor

Sheri D. Sheppard / Assistant Professor
TYPED NAME/TITLE OF ADVISING
PROFESSOR

LLD/sdp 4710C

ATTACHMENT A
CERTIFICATION OF ACADEMIC PROGRESS

Fellow : Mr. David A. Wagner
University : Stanford University
Subcontract : S-789-000-009

PART 1 COURSES : Spring Quarter 88-89

<u>Units</u>	<u>Number</u>	<u>Course</u>	<u>Grade</u>
3	ME 239 C	Theor. and Comp. Inelasticity	P
3	ME 301	Thesis. PhD Dissertation - J.C. Simo	P
6	ME 301	Thesis. PhD Dissertation - S.D. Sheppard	P

PART 2 RESEARCH PROGRESS : Spring Quarter 88-89

Refined the testing plan for the summer program at Wright Research and Development Center. Fatigue, Fracture and Reliability Group that attempts to verify the theoretically derived S integral as a characterizing parameter for thermoinelastic fracture. Designed the heating and cooling elements required to generate a thermal gradient across the aluminum specimen.

Completed theoretical development of the nine node uncoupled thermoinelastic element for FEAP based on a linear pressure field and a quadratic displacement field within each element. Began verifying element behavior and accuracy on certain benchmark cases. Some verification efforts remain on this tool.

"I certify that all information
stated is correct and complete."

David A. Wagner 7 SEP 89

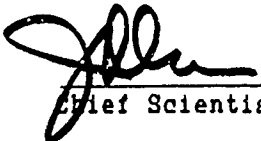
David A. Wagner

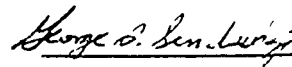
CONCURRENCE FORM

The Flight Dynamics Laboratory requests the continuation of the AFOSR fellowship for Mr. David A. Wagner, studying Damage Tolerance Characteristics of Advanced Structural Materials at Stanford University.

Give a brief statement of laboratory and/or Dr. George Sendecky (fellow's mentor) involvement with Mr. David A. Wagner.

Over the last two months, Mr. David A. Wagner has been planning and discussing with Dr. George P. Sendecky a test program to verify a new path independent integral as the crack driving force characterizing thermoinelastic fracture. Starting on 19 June 1989, he will be performing the planned experiments at the Flight Dynamics Laboratory. The experimental program will take 10 weeks to complete.

 26 June '89
Chief Scientist Date

 12 Jun 89
Mentor Date

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. David A. Wagner

University: Stanford University

Subcontract: S-789-000-009

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Please see Attachment A Part 1

2. Give a detailed description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Please see Attachment A Part 2

"I certify that all information
stated is correct and complete."

David A. Wagner 7 April 89
Signature/Fellowship Recipient

David A. Wagner
TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mr. David A. Wagner is making satisfactory academic progress toward a Ph.D. in the area of Damage Tolerance Characteristics of Advanced Structural Materials in the discipline of Applied Mechanics for the Winter 1989 quarter."

Sheri D. Sheppard
Signature/Advising Professor

Sheri D. Sheppard / Assistant Professor
TYPED NAME/TITLE OF ADVISING
PROFESSOR

LLD/sdp 4710C

ATTACHMENT A
CERTIFICATION OF ACADEMIC PROGRESS

Fellow : Mr. David A. Wagner
University : Stanford University
Subcontract : S-789-000-009

PART 1 COURSES : Winter Quarter 88-89

<u>Units</u>	<u>Number</u>	<u>Course</u>	<u>Grade</u>
3	ME 239 B	Theor. and Comp. Inelasticity	A
3	ME 240 A	Intro. Fracture of Solids	A
4	ME 301	Thesis, PhD Dissertation - J.C. Simo	P
4	ME 301	Thesis, PhD Dissertation - S.D. Sheppard	A

PART 2 RESEARCH PROGRESS : Winter Quarter 88-89

Proposed a testing plan to be conducted during ten week visit to Air Force Wright Aeronautical Laboratory, Fatigue, Fracture and Reliability Group under the guidance of Dr. George P. Sendeckyj. The tests will verify the path domain integral S as the crack driving force characterizing thermoinelastic fracture. The full plan calls for 58 test, 11 of which must be performed to meet the minimum testing objectives. The proposed plan is currently under review at AFWAL/FDSEC and at Stanford.

Implemented the finite element constitutive routines for small strain elasto-viscoplasticity for both plane stress and plane strain in simple four node displacement based element. Began developing nine node uncoupled thermoinelastic element for FEAP based on a linear pressure field within each element. This element will provide numerical simulations of selected tests and further S investigations.

"I certify that all information
stated is correct and complete."

David A. Wagner 7 April 89

David A. Wagner

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. David A. Wagner

University: Stanford University

Subcontract: S-789-C00-009

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Please see Attachment A Part 1

2. Give a detailed description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Please see Attachment A Part 2

"I certify that all information
stated is correct and complete."

David A. Wagner 10 JAN 89
Signature/Fellowship Recipient

David A. Wagner
TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mr. David A. Wagner is making satisfactory academic progress toward a Ph.D. in the area of Damage Tolerance Characteristics of Advanced Structural Materials in the discipline of Applied Mechanics for the Fall 1988 quarter."

Sheri D. Sheppard 1-11-89
Signature/Advising Professor

Sheri D. Sheppard / Assistant Professor
TYPED NAME/TITLE OF ADVISING
PROFESSOR

LLD/sdp 4710C

ATTACHMENT A
CERTIFICATION OF ACADEMIC PROGRESS

Fellow : Mr. David A. Wagner
University : Stanford University
Subcontract : S-789-000-009

PART 1 COURSES : Autumn Quarter 88-89

<u>Units</u>	<u>Number</u>	<u>Course</u>	<u>Grade</u>
3	ME 239 A	Theor. and Comp. Inelasticity	A
5	ME 291	Engineering Problems - S.D. Sheppard	A
5	ME 291	Engineering Problems - J.C. Simo	P
2	ME 292	Experimental Problems - S.D. Sheppard	A

PART 2 RESEARCH PROGRESS : Autumn Quarter 88-89

Successfully passed the PhD Qualifying Exam. Formed the reading committee that will guide and review the remainder of my research and dissertation.

Derived a path domain independent integral for coupled thermoelasticity based on the thermodynamic description. The formulation follows the from the Eshelby energy momentum tensor approach to describe the force on an elastic singularity generalized to the coupled thermoelastic problem. The discrete Lagrangian energy density provides the foundation for the integral conservation law.

"I certify that all information
stated is correct and complete."

David A. Wagner

David A. Wagner

CONCURRENCE FORM

The Materials Laboratory requests the continuation of the AFOSR fellowship for Mr. Dmitry Chizhik, studying Nondestructive Evaluation at Polytechnic University.

Give a brief statement of laboratory and/or Dr. Dale E. Chimest's (fellow's mentor) involvement with Mr. Dmitry Chizhik.

Mr. Chizhik is making excellent progress toward an advanced degree in Electrical Engineering at Polytechnic Inst. of NY under the direction of Prof. H. Bertoni.

Mr Chizhik has completed his course work very rapidly and is now performing graduate research on new configurations for acoustic microscope transducers and their behavior.

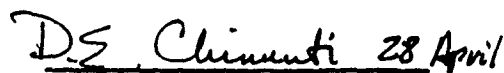
He has recently reported on his research at the IEEE Sonics and Ultrasonics Symposium. His Fellowship should definitely be continued.



Chief Scientist

04 MAY 1989

Date



Mentor

Date

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Dmitry Chizhik

University: Polytechnic University

Subcontract: S-789-000-010

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

None taken. Full time work on Dissertation.

2. Give a detailed description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

A novel acoustic microscope, called the slot-lens microscope, has been used to image graphite-epoxy composite samples. The microscope is described in D.A.Davids, P.Y.Wu and D.Chizhik, "Restricted Aperture Acoustic Microscope Lens for Rayleigh Wave Imaging", App.Phys.Lett., April 24, 1989. This instrument is capable of resolving anisotropy in materials. A study was begun to create a theoretical model of this microscope.

"I certify that all information stated is correct and complete."

Dmitry Chizhik
Signature/Fellowship Recipient

Dmitry Chizhik

TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mr. Dmitry Chizhik is making satisfactory academic progress toward a Ph.D. in the area of Nondestructive Evaluation in the discipline of Electrical Engineering for the Fall 1988-1989 semester."

Henry L. Bertoni
Signature/Advising Professor

Henry L. Bertoni, Professor

TYPED NAME/TITLE OF ADVISING
PROFESSOR

LLD/sdp 4661C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Rodger J. Biasca is making satisfactory academic progress toward a Ph.D. in the area of Space Physics in the discipline of Aeronautics and Astronautics for the Fall 1988 semester."

Daniel Hastings
Signature/Advising Professor

Daniel Hastings, Class of 1956 Career Development Associate Professor of
TYPED NAME/TITLE OF ADVISING Aeronautics and Astronautics
PROFESSOR

5025C

CONFERENCE FORM

The Rome Air Development Center requests the continuation of the AFOSR fellowship for Mr. Andrew B. Baker, studying Expert Systems (Vision) at Stanford University.

Give a brief statement of laboratory and/or Dr. Northrup Fowler's (fellow's mentor) involvement with Mr. Andrew B. Baker.

Mr. Baker continues to impress his professors and colleagues with the breadth and depth of his understanding of the theoretical issues associated with his research program at Stanford. He is, simply put, one of the best graduate student in CS at Stanford this decade.

Previous comments about the nature of the relationship between Mr. Baker and his laboratory sponsor remain valid.

Frederick J. Stannard

Chief Scientist

Date

Northrup Fowler 15 Aug 89

Mentor

Date

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Andrew B. Baker

Quarter: Spring 1989

University: Stanford University

Subcontract: S-789-000-012

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Computer Science 499. Advanced Reading and Research. Pass

(only offered pass/fail)

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Worked on developing thesis proposal in the general area of probabilistic inductive reasoning. Also, prepared a survey article "Nonmonotonic Temporal Reasoning" with Yoav Shoham, to appear.

"I certify that all information stated is correct and complete."

Andrew B. Baker
Signature/Fellowship Recipient

Andrew B. Baker
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4956C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Andrew B. Baker is making satisfactory academic progress toward a Ph.D. in the area of Expert Systems in the discipline of Computer Science for the Spring 1989 quarter."

Genesereth
Signature/Advising Professor

Michael R. Genesereth, Associate Professor of Computer Science
TYPED NAME/TITLE OF ADVISING
PROFESSOR

4956C

CONCURRENCE FORM

The Rome Air Development Center requests the continuation of the AFOSR fellowship for Mr. Andrew B. Baker, studying Expert Systems (Vision) at Stanford University.


Give a brief statement of laboratory and/or Dr. Northrup Fowler's (fellow's mentor) involvement with Mr. Andrew B. Baker.

Mr. Baker's graduate career at Stanford continues apace. He has passed both the computer science comprehensive exam and the AI qualifying exam. He is in the process of preparing a thesis proposal and assembling a committee. This academic year he has had three papers published in refereed journals. Three Stanford senior scientists, including the Computer Science Department Chairman, have given me glowing accounts of Mr. Baker's research.

Mr. Baker has had, and continues to have, no direct scientific or technical involvement with either RADC or his laboratory mentor. He has deflected all overtures to get more closely involved with AI activities at RADC on the grounds that his primary research objectives are best served at this moment by remaining totally within the Stanford environment.



Chief Scientist Date

 12 May 8

Mentor Date

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Andrew B. Baker

Quarter: Winter 1989

University: Stanford University

Subcontract: S-789-000-012

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Computer Science 499. Advanced Reading and Research. 12 units. Pass.

(only offered pass/fail)

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Produced final versions of 3 papers: "A Simple Solution to the Yale Shooting Problem" (to appear in Knowledge Representation'89), "Temporal Projection and Explanation",

and "A Theorem Prover for Prioritized Circumscription" (the last two, coauthored with M.L. Ginsberg, and to appear in IJCAI-89).

Satisfied teaching requirements by serving as the teaching assistant for a graduate course in Artificial Intelligence.

Began work on a thesis proposal, in the area of inductive learning and metalevel reasoning.

XR

"I certify that all information stated is correct and complete."

Andrew B. Baker

Signature/Fellowship Recipient

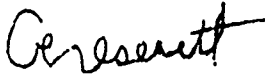
Andrew B. Baker

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4956C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Andrew B. Baker is making satisfactory academic progress toward a Ph.D. in the area of Expert Systems in the discipline of Computer Science for the Winter 1989 quarter."



Signature/Advising Professor

Michael R. Genesereth, Associate Professor of Computer Science

TYPED NAME/TITLE OF ADVISING
PROFESSOR

4956C

CONCURRENCE FORM

The Rome Air Development Center requests the continuation of the AFOSR fellowship for Mr. Andrew B. Baker, studying Expert Systems (Vision) at Stanford University.

Give a brief statement of laboratory and/or Dr. Northrup Fowler's (fellow's mentor) involvement with Mr. Andrew B. Baker.

To be brutally frank, Mr. Baker has had no direct involvement with either RADC or his RADC mentor, Dr. Northrup Fowler III, other than to exchange letters or electronic mail from time to time. Mr. Baker is on an academic "fast track." He has passed his qualifying exams in near record time, is already doing original research and is viewed by the Stanford Computer Science faculty as the best graduate student in his class. Dr. Nils Nilsson, the chairman of the Computer Science Department at Stanford wrote to Dr. Fowler in June 1988,

"Andrew Baker is super! He is already doing research as a first-year student comes to my research meetings, is taking a class I am teaching, and is impressing everybody!! The AF couldn't have picked a better 'Fellow'."

In short, Mr. Baker has all the academic qualities of an outstanding scholar. The generosity of the Air Force, through this fellowship, will be repaid many times over in the future by discoveries and research contributions of very gifted young people like Mr. Baker.

The obvious down-side is the loss of near-term return through close interaction with the laboratory, which doesn't seem realistic for the very best people at the very best universities. How to reconcile this fact with the goals of this program is a question I leave to others. If it is important for the Air Force to establish contact with the most promising scientists of the next generation, then Mr. Baker seems a good bet!

Ted Diamond 21 Feb 89

Chief Scientist

Date

Northrup Fowler III 16 Feb 89

Mentor

Date

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Andrew B. Baker

Quarter: Autumn 1988

University: Stanford University

Subcontract: S-789-000-012

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

CS 499. ~~Independent~~ Reading and Research. 12 Units. Pass.

(this course is a pass/fail course.)

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

This quarter, I passed the Artificial Intelligence Qualifying Exam with distinction. Most of my time was spent studying for this exam. A paper of mine written last school year, "A Simple Solution to the Yale Shooting Problem," was accepted for publication by The First International Conference on Knowledge Representation and Reasoning to be held in Toronto, May 1989. Some time was spent on revising this paper. Two other papers (written jointly with Dr. Matthew L. Ginsberg), "Temporal Projection and Explanation" and "A Theorem Prover for Prioritized Circumscription," have been completed and submitted for publication. Presently, I am reading various articles for the purposes of choosing a suitable thesis topic.

"I certify that all information stated is correct and complete."

Andrew B. Baker
Signature/Fellowship Recipient

Andrew B. Baker

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4956C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Andrew B. Baker is making satisfactory academic progress toward a Ph.D. in the area of Expert Systems in the discipline of Computer Science for the Autumn 1988 quarter."

Signature/Advising Professor

Genesereth

TYPED NAME/TITLE OF ADVISING
PROFESSOR

Michael R. Genesereth, Associate Professor of Computer Science

4956C

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Andrew C. Bartlett

Semester: Summer 1989

University: University of Massachusetts

Subcontract: S-789-000-013

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

See attached sheets

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

See attached sheets

"I certify that all information stated is correct and complete."

Andrew C. Bartlett
Signature/Fellowship Recipient

Andrew C. Bartlett
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5202C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Andrew C. Bartlett is making satisfactory academic progress toward a Ph.D. in the area of Nonlinear Flight Mechanics with Emphasis on Robust Flight Control in the discipline of Electrical Engineering for the Summer 1989 semester."

Christopher V. Hollot
Signature/Advising Professor

C. V. Hollot, Assistant Professor
TYPED NAME/TITLE OF ADVISING
PROFESSOR

4888C

1. Courses taken while in PhD program.

Dept.	No.	Course Title	Credits	Grade
Fall 1986				
ECE	608	SIGNAL THEORY I	3	A
ECE	785A	STOCHASTIC CONTROL	3	AB
MATH	411	ABSTRACT ALGEBRA I	3	A
MATH	597A	MATHEMATICAL ANALYSIS	3	A
ECE	793	SEMINAR	1	Satisfactory
Spring 1987				
ECE	785A	ADAPTIVE CONTROL	3	A
ECE	785B	ROBUST CONTROL	3	A
ECE	899	PH D DISSERTATION	4	In Progress
ECE	794	SEMINAR	1	Satisfactory
Fall 1987				
MATH	623	REAL ANALYSIS I	3	B
MATH	671	TOPOLOGY I	3	AB
ECE	597G	ROBOTIC: ANAL & CONT		Audit
ECE	899	PH D DISSERTATION	3	In Progress
ECE	793	SEMINAR	1	Satisfactory
Spring 1988				
MATH	624	REAL ANALYSIS II		Audit
ECE	899	PH D DISSERTATION	9	In Progress
ECE	794	SEMINAR	1	Satisfactory
Fall 1988				
ECE	899	PH D DISSERTATION	9	In Progress
ECE	794	SEMINAR	1	Satisfactory
Spring 1989				
ECE	899	PH D DISSERTATION	9	In Progress
ECE	794	SEMINAR	1	Satisfactory

2. Research and Progress Toward Dissertation

During the summer semester 1988, I continued to do research in the area of robust control. This research focused on the analysis and control of systems with parametrically described uncertainties. Approximately three-fourths of the research results which will comprise my dissertation have been completed. Part of this time was spent writing papers for conferences and journals.


CONCURRENCE FORM

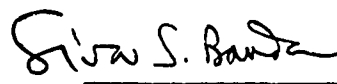
The Flight Dynamics Laboratory requests the continuation of the AFOSR fellowship for Mr. Andrew C. Bartlett, studying Nonlinear Flight Mechanics at The University of Massachusetts.

Give a brief statement of laboratory and/or Dr. Siva Banda's (fellow's mentor) involvement with Mr. Andrew C. Bartlett.

Mr Andrew Bartlett's technical contributions in the area of robust control have been outstanding. He spent the Summer of 1988 in the Flight Dynamics Laboratory working with Dr Siva Banda. Their work resulted in a conference paper and a journal paper. Since then, Dr Banda interacts with Mr Bartlett over the telephone regarding the state of the research in this general area. Mr Bartlett also receives copies of the papers that Dr Banda's Group writes for various conferences and journals. Mr Bartlett's increased interest on the problem of parametric uncertainty and robust control is a direct consequence of Dr Banda's involvement with him.

The Flight Dynamics Laboratory is extremely pleased with Mr Bartlett's accomplishments.

 21 Jun '89
Chief Scientist Date

 8 Jun 89
Mentor Date

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Andrew C. Bartlett

Semester: Spring 1989

University: University of Massachusetts

Subcontract: S-789-000-013

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

See attached sheets

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

See attached sheets

"I certify that all information stated is correct and complete."


Signature/Fellowship Recipient

Andrew C. Bartlett
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5202C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Andrew C. Bartlett is making satisfactory academic progress toward a Ph.D. in the area of Nonlinear Flight Mechanics with Emphasis on Robust Flight Control in the discipline of Electrical Engineering for the Spring 1989 semester."


Signature Advising Professor

C. V. Hollot, Assistant Professor
TYPED NAME/TITLE OF ADVISING
PROFESSOR

4888C

1. Courses taken while in PhD program.

Dept.	No.	Course Title	Credits	Grade
Fall 1986				
ECE	608	SIGNAL THEORY I	3	A
ECE	785A	STOCHASTIC CONTROL	3	AB
MATH	411	ABSTRACT ALGEBRA I	3	A
MATH	597A	MATHEMATICAL ANALYSIS	3	A
ECE	793	SEMINAR	1	Satisfactory
Spring 1987				
ECE	785A	ADAPTIVE CONTROL	3	A
ECE	785B	ROBUST CONTROL	3	A
ECE	899	PH D DISSERTATION	4	In Progress
ECE	794	SEMINAR	1	Satisfactory
Fall 1987				
MATH	623	REAL ANALYSIS I	3	B
MATH	671	TOPOLOGY I	3	AB
ECE	597G	ROBOTIC: ANAL & CONT		Audit
ECE	899	PH D DISSERTATION	3	In Progress
ECE	793	SEMINAR	1	Satisfactory
Spring 1988				
MATH	624	REAL ANALYSIS II		Audit
ECE	899	PH D DISSERTATION	9	In Progress
ECE	794	SEMINAR	1	Satisfactory
Fall 1988				
ECE	899	PH D DISSERTATION	9	In Progress
ECE	794	SEMINAR	1	Satisfactory
Spring 1989				
ECE	899	PH D DISSERTATION	9	In Progress
ECE	794	SEMINAR	1	Satisfactory

2. Research and Progress Toward Dissertation

During the spring semester 1988, I continued to do research in the area of robust control. This research focused on the analysis and control of systems with parametrically described uncertainties. Approximately one half to two thirds of the research results which will comprise my dissertation have been completed. Part of this time was spent writing portions of my proposal and dissertation.

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Andrew C. Bartlett

Semester: Fall 1988

University: University of Massachusetts

Subcontract: S-789-000-013

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

See Attached Sheets

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

See Attached Sheets

"I certify that all information stated is correct and complete."



Signature/Fellowship Recipient

Andrew C. Bartlett

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5202C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Andrew C. Bartlett is making satisfactory academic progress toward a Ph.D. in the area of Nonlinear Flight Mechanics with Emphasis on Robust Flight Control in the discipline of Electrical Engineering for the Fall 1988 semester."


Signature/Advising Professor

C. V. Hollot, Assistant Professor
TYPED NAME/TITLE OF ADVISING
PROFESSOR

4888C

1. Courses taken while in PhD program.

Dept.	No.	Course Title	Credits	Grade
Fall 1986				
ECE	608	SIGNAL THEORY I	3	A
ECE	785A	STOCHASTIC CONTROL	3	AB
MATH	411	ABSTRACT ALGEBRA I	3	A
MATH	597A	MATHEMATICAL ANALYSIS	3	A
ECE	793	SEMINAR	1	Satisfactory
Spring 1987				
ECE	785A	ADAPTIVE CONTROL	3	A
ECE	785B	ROBUST CONTROL	3	A
ECE	899	PH D DISSERTATION	4	In Progress
ECE	794	SEMINAR	1	Satisfactory
Fall 1987				
MATH	623	REAL ANALYSIS I	3	B
MATH	671	TOPOLOGY I	3	AB
ECE	597G	ROBOTIC: ANAL & CONT		Audit
ECE	899	PH D DISSERTATION	3	In Progress
ECE	793	SEMINAR	1	Satisfactory
Spring 1988				
MATH	624	REAL ANALYSIS II		Audit
ECE	899	PH D DISSERTATION	9	In Progress
ECE	794	SEMINAR	1	Satisfactory
Fall 1988				
ECE	899	PH D DISSERTATION	9	In Progress
ECE	794	SEMINAR	1	Satisfactory

2. Research and Progress Toward Dissertation

During the fall semester 1988, I continued to do research in the area of robust control. This research focused on the analysis and control of systems with parametrically described uncertainties.

Approximately one half to two thirds of the research results which will comprise my dissertation have been completed. Part of this time was spent writing portions of my proposal and dissertation.

CONCURRENCE FORM

The Human Research Laboratory requests the continuation of the AFOSR fellowship for Ms. Emily Dibble, studying Cognitive Psychology/Basic Skills at The University of Washington.

Give a brief statement of laboratory and/or Dr. Sherrie P. Gott's (fellow's mentor) involvement with Ms. Emily Dibble.

Ms Dibble has been sent recent draft manuscripts emanating from the Basic Job Skills Research Program and encouraged to comment on reported methodologies and findings. In addition she has been encouraged to plan to fulfill an on-site internship here with BTS scientists in the summer of 1990.

William D. Welch *20 Apr 89*
Chief Scientist Date
B. E. Welch *30 Apr 89*

Sherrie P. Gott *24 Apr 89*
Mentor Date

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Ms. Emily Dibble is making satisfactory academic progress toward a Ph.D. in the area of Cognitive Psychology/Basic Skills in the discipline of Behavioral Science for the *Fall* 1988 quarter."

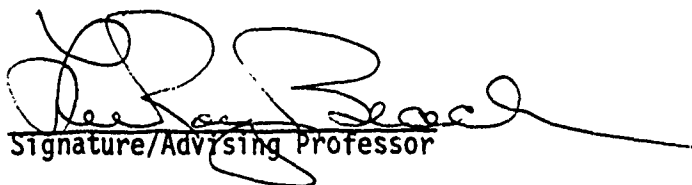

Signature/Advising Professor

Lee Roy Beach, Professor
TYPED NAME/TITLE OF ADVISING
PROFESSOR

4888C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Ms. Emily Dibble is making satisfactory academic progress toward a Ph.D. in the area of Cognitive Psychology/Basic Skills in the discipline of Behavioral Science for the Winter 1989 quarter."



Signature/Advising Professor

Lee Roy Beach, Professor
TYPED NAME/TITLE OF ADVISING
PROFESSOR

4888C

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Ms. Emily Dibble

QUARTER: Fall 1988

University: University of Washington

Subcontract: S-789-000-014

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Seminar in cognitive processes	credit
Independent studies/reading	"
cognitive Journal club	credit
Independent research	"

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Designing pilot research for dissertation proposal

Revising proposal for qualifying exam

"I certify that all information stated is correct and complete."

Emily Dibble
Signature/Fellowship Recipient

EMILY DIBBLE
TYPED NAME/FELLOWSHIP RECIPIENT

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Ms. Emily Dibble

QUARTER: Winter 1989

University: University of Washington

Subcontract: S-789-000-014

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Psychology Psychology of Reading	3.5
Independent Study	credit
Seminar in Cognitive Processes	credit
Independent Study	4.0

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Pilot study on the relative perceived difficulty
of algebra story problems and algebraic systems
of equations
Developing methodology for studying the role of
phonology in reading comprehension

"I certify that all information stated is correct and complete."


Signature/Fellowship Recipient

EMILY DIBBLE
TYPED NAME/FELLOWSHIP RECIPIENT

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Ms. Helen E. Gainey

Semester: Summer 1989

University: Clemson University

Subcontract: S-789-000-015

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

<u>Course</u>	<u>Description</u>	<u>Grade</u>
Ch E 803	Advanced Transport Phenomena	A
Ch E 804	Chemical Engineering Thermodynamics	B
Ch E 805	Chemical Engineering Kinetics	B
Ch E 814	Applied Numerical Methods in Process Simulation	A
Ch E 823	Mass Transfer and Stagewise Contact Operations	A
E M 630	Mechanics of Composite Materials	A
E M 831	Theory of Elasticity I	A
Mthsc 634	Advanced Engineering Mathematics	A
Mthsc 800	Probability	A
E M 845	Intermediate Dynamics	A

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Please see attached sheet

"I certify that all information stated is correct and complete."

Helen E. Gainey
Signature/Fellowship Recipient

Helen Elizabeth Gainey
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4957C.


Qualifying examinations for the Ph. D. degree were successfully completed in May 1988. The remainder of this year was spent spinning, heat-treating, and testing circular and trilobal fibers of equivalent cross-sectional area. This work confirmed the phenomena of increased strength on variation of cross-sectional shape. The results of this work were presented at the International Carbon Conference (Newcastle, UK) and the Fibertex Conference (Greenville, S. C.) in the fall of 1988.

During the spring of 1989, the single filament data analysis methods were developed in more detail. Two methods have been developed thus far. The first, and most important, method is a bimodal Weibull analysis which will yield parameters spanning data at all gauge lengths of a given shape. This allows discerning between two different failure modes, the relative severity of each, and their contribution to the failure frequency at each gauge length. By comparing the results for different shapes, some indication of a change in flaw distribution and failure mode resulting from a change in shape should be apparent. The second analysis method which will be used is a distribution based on brittle failure theory which assumes all failure occurs at surface flaws. The quality of the fit obtained from this method will be used to indicate how well this assumption is upheld for each shape.

Currently, circular, trilobal, and c-shape pitch-based carbon fibers are being produced and tested by the single filament method. These fibers have equivalent thicknesses so that any differences in strength due to differing heat treatment conditions seen by interior portions of the various shapes should be negligible. The data will be analyzed by the methods described above to compare strength and fiber quality. In the fall of 1989, the fabrication and testing of unidirectional composites from fibers of these three shapes will begin as the first step in investigating the effect of fiber shape on composite performance.

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Ms. Helen E. Gainey is making satisfactory academic progress toward a Ph.D. in the area of Materials Science in the discipline of Engineering for the Summer 1989 semester."


Signature/Advising Professor

Danny D. Edie/Professor of Chemical Engineering
TYPED NAME/TITLE OF ADVISING
PROFESSOR

4957C

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Ms. Helen E. Gainey

Semester: Spring 1989

University: Clemson University

Subcontract: S-789-000-015

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

<u>Course</u>	<u>Description</u>	<u>Grade</u>
Ch E 803	Advanced Transport Phenomena	A
Ch E 804	Chemical Engineering Thermodynamics	B
Ch E 805	Chemical Engineering Kinetics	B
Ch E 814	Applied Numerical Methods in Process Simulation	A
Ch E 823	Mass Transfer and Stagewise Contact Operations	A
E M 630	Mechanics of Composite Materials	A
E M 831	Theory of Elasticity I	A
Mthsc 634	Advanced Engineering Mathematics	A
Mthsc 800	Probability	A

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Please see attached sheet

"I certify that all information stated is correct and complete."

Helen E. Gainey
Signature/Fellowship Recipient

Helen E. Gainey
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4957C

The first phase of this research project involves investigating the effect cross-sectional shape on pitch-based carbon fiber performance. Round and trilobal fibers were spun, heated-treated, and subjected to single filament testing to determine ultimate tensile strength. The data was analyzed using a statistical distribution based on Weibull theory. The results were published in two articles: **Failure Analysis of Pitch-Based Carbon Fibers** (Fibertext Conference, Proceedings, September, 1988) and **Flaw Distributions in Noncircular Carbon Fibers** (International Carbon Conference, Proceedings, September, 1988). This study confirms the findings of initial research which indicate that certain noncircular fibers are stronger than circular fibers. In addition, it has led us to believe that valuable information on the effect of shape can be gained by analyzing the data using a variety of distributions which are based on different assumptions about flaw distributions and failure mechanisms. By comparing the quality of the fits obtained from each distribution, we should be able to determine which assumptions are most appropriate for a given shape. This phase of the research project should be completed during the summer of 1989.

The second phase of the project deals with determining the effect of fiber shape on composite performance. Fabrication and testing of unidirectional composite sample should begin in the fall of 1989. It is expected that the failure of the composite samples will be modeled using finite element analysis and the results of single filament testing obtained in Phase I.

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Ms. Helen E. Gainey is making satisfactory academic progress toward a Ph.D. in the area of Materials Science in the discipline of Engineering for the Spring 1989 semester."


Signature/Advising Professor

Danny D. Edie

TYPED NAME/TITLE OF ADVISING
PROFESSOR

4957C

CONCURRENCE FORM

The School of Aerospace Medicine requests the continuation of the AFOSR fellowship for Mr. Edward Gellenbeck, studying Knowledge Acquisition and Artificial Intelligence Techniques at Oregon State University.

Give a brief statement of laboratory and/or Dr Albanese's- (fellow's mentor) involvement with Mr. Edward Gellenbeck.

I spoke at some length with Prof. Cook and feel that this effort is properly underway. It's an effort in programming methodology which I feel is quite important.

George Chuoh

Chief Scientist

Date

30 OCT 89

Albanese

24 Oct 89

Mentor

Date

S-789-000-016

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Edward M. Gellenbeck

Semester: Summer 1989

University: Oregon State University

Subcontract: S-789-000-016

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

CS 503 -- Thesis Credit

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Continue work on beacons and program comprehension

"I certify that all information stated is correct and complete."

Edward M. Gellenbeck
Signature/Fellowship Recipient

Edward M. Gellenbeck
TYPED NAME/FELLOWSHIP RECIPIENT

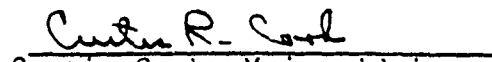
LLD/sdp 5079C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Edward M. Gellenbeck is making satisfactory academic progress toward a Ph.D. in the area of Knowledge Acquisition and Artificial Intelligence Techniques in the discipline of Computer Science for the Summer 1989 quarter."


Signat: re/Advising Professor

Walter Rudd, Professor and Chairman Walter Rudd, Chairman
TYPED NAME/TITLE OF ADVISING
PROFESSOR


Curtis Cook, Major Advisor

5079C

CONCURRENCE FORM

The School of Aerospace Medicine requests the continuation of the AFOSR fellowship for Mr. Edward M. Gellenbeck, studying Knowledge Acquisition and Artificial Intelligence at Oregon State University.

Give a brief statement of laboratory and/or Dr. Albanese (fellow's mentor) involvement with Mr. Edward M. Gellenbeck.

I have exchanged information with Dr. Curtis Cook who is Edward's faculty advisor. Ed seems to be progressing well with his thesis. I view what Ed is doing in his doctoral research to be very important in my work environment. He is attempting to determine those factors in computer programming which enhance program comprehension. A good deal of our time importing and exporting code is spent studying documentation to understand what the code is doing. If this comprehension time can be reliably reduced a substantive pay back would result.

George Chuoh 26SEP89
Acting Chief Scientist Date

L. Albanese 19 Sep 89
Mentor Date

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Edward M. Gellenbeck

Semester: Spring 1989

University: Oregon State University

Subcontract: S-789-000-016

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

ST453 -- Experimental Design

Grade: 'A'

CS503 -- Thesis

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Continued looking at the role of beacons in program comprehension.

Conducted a pilot study designed to use experienced programmers to identify ~~programmers~~ beacons

"I certify that all information stated is correct and complete."

Edward M. Gellenbeck
Signature/Fellowship Recipient

Edward M. Gellenbeck
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5079C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Edward M. Gellenbeck is making satisfactory academic progress toward a Ph.D. in the area of Knowledge Acquisition and Artificial Intelligence Techniques in the discipline of Computer Science for the Spring 1989 quarter."

Walter Rudd
Signature/Advising Professor

WALTER RUDD PROFESSOR and CHAIRMAN
TYPED NAME/TITLE OF ADVISING
PROFESSOR

Walter Rudd, Chairman

Curtis R. Cook
Curtis Cook, Major Advisor

5079C

CONCURRENCE FORM

The School of Aerospace Medicine requests the continuation of the AFOSR fellowship for Mr. Edward M. Gellenbeck, studying Knowledge Acquisition and Artificial Intelligence at Oregon State University.

Give a brief statement of laboratory and/or Dr. Albanese (fellow's mentor) involvement with Mr. Edward M. Gellenbeck.

My interaction with Mr. Gellenbeck is by telephone and by exchange of reprints. Mr. Gellenbeck is working on the very important problem of how to make computer programs intelligible and transposable from one computer science setting to another to include the naive computer user. My research group needs the product Mr. Gellenbeck is attempting to develop in his Ph.D. work. The browsing tool concept is a good one, but, in my opinion the concept of program beacons may be better. Empirical tests will tell, and Mr. Gellenbeck is pursuing these. I wish to stay fully abreast of Mr. Gellenbeck's progress, and I ask him to send me key literature, and write-up's he has completed in preliminary form.

SSgt E. Volk 4 May 39

Chief Scientist

Date _____

Richard G. Albansen mo 26 April 85

Mentor

Date _____

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Edward M. Gellenbeck

Semester: Fall 1988

University: Oregon State University

Subcontract: S-789-000-016

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Thesis CS503 - Credit 8 hrs

ST 451 - Statistical Methods for Research Workers
4 hrs 'A'

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Completed prototype browsing system for software documentation
Empirical testing of system with undergrad and
graduate students

"I certify that all information stated is correct and complete."

Edward M. Gellenbeck
Signature/Fellowship Recipient

Edward M. Gellenbeck
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5079C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Edward M. Gellenbeck is making satisfactory academic progress toward a Ph.D. in the area of Knowledge Acquisition and Artificial Intelligence Techniques in the discipline of Computer Science for the Fall 1988 quarter."



Signature/Advising Professor

WALTER L. RUDD PROFESSOR & CHAIRMAN

TYPED NAME/TITLE OF ADVISING
PROFESSOR

Walter J. Rudd



Curtis Cook, Major Advisor

5079C

CONCURRENCE FORM

The Materials Laboratory requests the continuation of the AFOSR fellowship for Mr. Michael A. Hubbard, studying Nonlinear Optics at Northwestern University.

Give a brief statement of laboratory and/or Dr. Griffith's (fellow's mentor) involvement with Mr. Michael A. Hubbard.

Mr. Hubbard's work is well within the type of efforts and interests of this Laboratory. The materials and the concept of engineered nonlinear optical properties is sound and deserves continued support.

John M. Bate 8 Mar 89

Chief Scientist

Date

Gordon H. Griffith 7 Mar

Mentor

Date

GORDON H. GRIFFITH, Chief
Electronic and Optical Materials Branch
Electromagnetic Materials & Survivability Div
Materials Laboratory

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Michael A. Hubbard

Quarter: Winter 1989

University: Northwestern University

Subcontract: S-789-000-017

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

see attached

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

see attached

"I certify that all information stated is correct and complete."

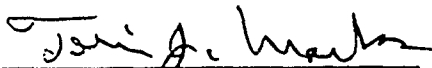
Michael A. Hubbard
Signature/Fellowship Recipient

Michael A. Hubbard
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4959C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Michael A. Hubbard is making satisfactory academic progress toward a Ph.D. in the area of Nonlinear Optics in the discipline of Chemistry for the Summer 1989 quarter."


Signature/Advising Professor

Tobin J. Marks/Professor of Chemistry
TYPED NAME/TITLE OF ADVISING
PROFESSOR

4959C

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Michael A. Hubbard

Quarter: Spring 1989

University: Northwestern University

Subcontract: S-789-000-017

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

see attached

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

see attached

"I certify that all information stated is correct and complete."


Michael A. Hubbard
Signature/Fellowship Recipient

Michael A. Hubbard
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4959C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Michael A. Hubbard is making satisfactory academic progress toward a Ph.D. in the area of Nonlinear Optics in the discipline of Chemistry for the Spring 1989 quarter."


Signature/Advising Professor

Tobin J. Marks/Professor of Chemistry
TYPED NAME/TITLE OF ADVISING
PROFESSOR


4959C

CONCURRENCE FORM

The Materials Laboratory requests the continuation of the AFOSR fellowship for Mr. Michael A. Hubbard, studying Nonlinear Optics at Northwestern University.

Give a brief statement of laboratory and/or Dr. Griffith's (fellow's mentor) involvement with Mr. Michael A. Hubbard.

Aside from the visit to W-P in May, interaction has been minimal. Changing the mentor to Dr. Ken Hephkins will provide an opportunity for more direct contacts, since Ken is totally focused on the NLO area and will take time to interface. A summer stay at ML for some hands on research is also desirable.


Chief Scientist 18 DEC 89
Date

 14 Dec 89
Mentor Date

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Michael A. Hubbard

Quarter: Summer 1989

University: Northwestern University

Subcontract: S-789-000-017

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

see attached

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

see attached.

"I certify that all information stated is correct and complete."

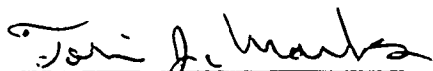
Michael A. Hubbard
Signature/Fellowship Recipient

Michael A. Hubbard
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4959C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Michael A. Hubbard is making satisfactory academic progress toward a Ph.D. in the area of Nonlinear Optics in the discipline of Chemistry for the Winter 1989 quarter."


Signature/Advising Professor

Tobin J. Marks/Professor of Chemistry
TYPED NAME/TITLE OF ADVISING
PROFESSOR

4959C

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Michael A. Hubbard

Quarter: Spring 1989

University: Northwestern University

Subcontract: S-789-000-017

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

see attached

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

see attached

"I certify that all information stated is correct and complete."


Michael A. Hubbard
Signature/Fellowship Recipient

Michael A. Hubbard
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4959C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Michael A. Hubbard is making satisfactory academic progress toward a Ph.D. in the area of Nonlinear Optics in the discipline of Chemistry for the Spring 1989 quarter."


Signature/Advising Professor

Tobin J. Marks/Professor of Chemistry
TYPED NAME/TITLE OF ADVISING
PROFESSOR

4959C

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Michael A. Hubbard

Quarter: Winter 1989

University: Northwestern University

Subcontract: S-789-000-017

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

see attached

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

see attached

"I certify that all information stated is correct and complete."

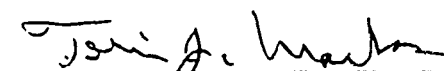
Michael A. Hubbard
Signature/Fellowship Recipient

Michael A. Hubbard
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4959C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Michael A. Hubbard is making satisfactory academic progress toward a Ph.D. in the area of Nonlinear Optics in the discipline of Chemistry for the Summer 1989 quarter."


Signature/Advising Professor

Tobin J. Marks/Professor of Chemistry
TYPED NAME/TITLE OF ADVISING
PROFESSOR

4959C

Presentations made in compliance with Ph.D. requirements.

1. Divisional Seminar

Halide glasses: structures and properties

February 10, 1989

2. Original Research Proposal

Synthesis and Characterization of Boron Phosphides
by Pyrolysis of a Preceramic Polymer.

May 2, 1989

Other Presentations

1. Seminar

Poled Polymeric Nonlinear Optical Materials

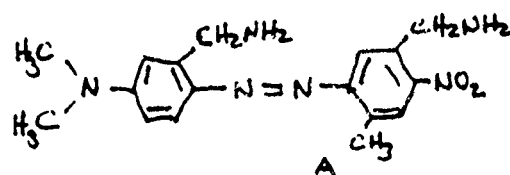
Wright Patterson AFB

May 26, 1989

Summary of Research Winter 1989 through Summer 1989.

We have previously shown that optically transparent epoxy may be doped with a non-reactive nonlinear optical chromophore and then simultaneously electrically poled and chemically crosslinked. The resulting crosslinked and poled polymer matrices display great temporal stability (as determined by second harmonic generation) compared to other poled polymer systems in which the chromophore is not connected to the host polymer. We believe that the temporal stability will be enhanced still further by chemical bonding the chromophores into the crosslinking epoxy matrix. Chromophores suitable for incorporation into the crosslinking epoxy are not commercially available. Thus this phase of our research has been directed at synthesizing a chromophore that contains functional groups that will chemically incorporate the chromophore into the crosslinking epoxy matrix.

The target chromophore A was chosen for several reasons.



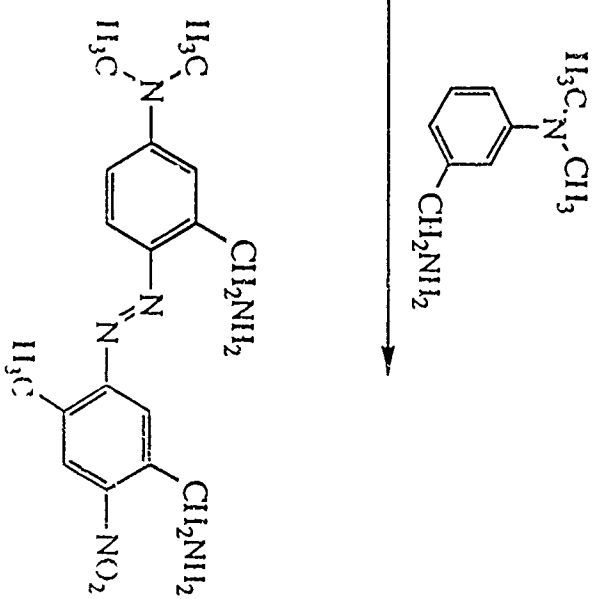
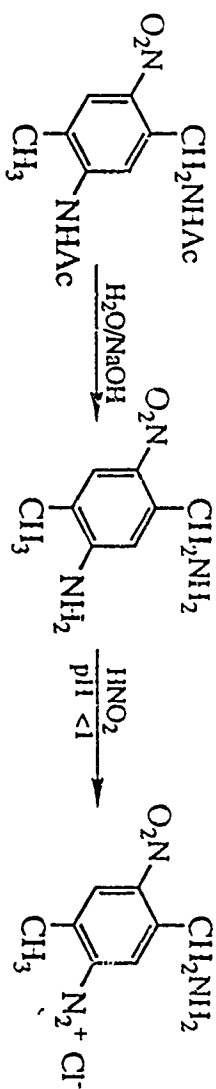
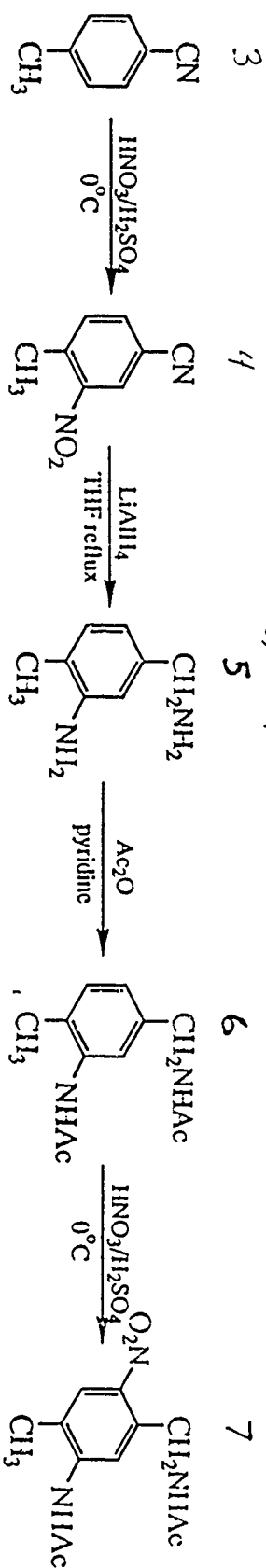
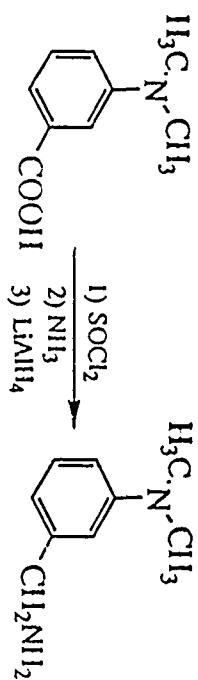
- 1) Substituted azobenzenes with electron donating (dimethylamino) and electron withdrawing (nitro) groups opposite each other are convenient for the laser system used here.
- 2) Aliphatic amine reactive groups were chosen to minimize interaction with the electronic structure of the remainder of the molecule. The presence of an aromatic amine moiety on the same phenyl ring as the nitro group could greatly affect the chromophore's charge transfer ability. The aliphatic nature of the reactive groups is also chemically similar to the amine curing component (believed to be aliphatic).
- 3) Two aliphatic amine groups were chosen so that the chromophore would indeed be polyfunctional and incorporated into the crosslinking matrix as an internal member and not simply as an end member.

The synthetic scheme followed is shown on the attached figure.

- 1) Compounds 1 and 3 are commercially available.
- 2) Compound 2 is prepared from 1 by reaction with thionyl chloride in chloroform to give the substituted benzoyl chloride (not isolated). The acyl chloride was amidated by bubbling ammonia gas through the solution. The amide was recovered and reduced to the benzylamine with lithium aluminum hydride.
- 3) Compound 4 is prepared from 3 by reaction with ice cold nitric acid/sulfuric acid.

- 4) Compound 5 is prepared from 4 by reduction with lithium aluminum hydride in refluxing THF. Yield is approximately 50 percent.
- 5) Compound 6 is prepared by stirring 4 with acetic anhydride pyridine. The diamide precipitates from solution and may be filtered off and rinsed with ether.
- 6) Nitration of 6 takes place in nitric acid/sulfuric acid at degrees C for 3 hours. Nitration occurs both ortho and para the acetanilide (NHAc) moiety. This was unexpected as acetanilide is usually a strong para director. Currently we are preparing bulkier diamides using isobutyric anhydride and trimethylacetic anhydride in order to sterically hinder the ortho position.
- 7) Deamidation of the nitrated diamides proceeds with decomposition if performed under basic conditions as shown in the figure. Hydrolysis to the dihydrochloride salt does take place by refluxing in 2N HCl for 12 hours.
- 8) The diazotization and coupling reactions have been attempted using compounds 2 and 5 at pH 2. The product was not purified but the expected change from colorless starting materials to a dark red product that was observed (to be expected with this sort of system) strongly suggests that coupling occurred.

1 2



CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Michael A. Hubbard

Quarter: Summer 1989

University: Northwestern University

Subcontract: S-789-000-017

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

see attached

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

see attached.

"I certify that all information stated is correct and complete."

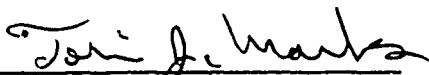

Signature/Fellowship Recipient

Michael A. Hubbard
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4959C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Michael A. Hubbard is making satisfactory academic progress toward a Ph.D. in the area of Nonlinear Optics in the discipline of Chemistry for the Winter 1989 quarter."


Signature/Advising Professor

Tobin J. Marks/Professor of Chemistry
TYPED NAME/TITLE OF ADVISING
PROFESSOR

4959C

Presentations made in compliance with Ph.D. requirements.

1. Divisional Seminar

Halide glasses: structures and properties

February 10, 1989

2. Original Research Proposal

Synthesis and Characterization of Boron Phosphides
by Pyrolysis of a Preceramic Polymer.

May 2, 1989

Other Presentations

1. Seminar

Poled Polymeric Nonlinear Optical Materials

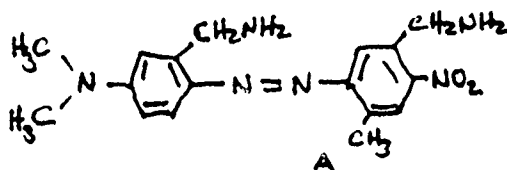
Wright Patterson AFB

May 26, 1989

Summary of Research Winter 1989 through Summer 1989.

We have previously shown that optically transparent epoxy may be doped with a non-reactive nonlinear optical chromophore and then simultaneously electrically poled and chemically crosslinked. The resulting crosslinked and poled polymer matrices display greater temporal stability (as determined by second harmonic generation) compared to other poled polymer systems in which the chromophore is not connected to the host polymer. We believe that this temporal stability will be enhanced still further by chemically bonding the chromophores into the crosslinking epoxy matrix. Chromophores suitable for incorporation into the crosslinking epoxy are not commercially available. Thus this phase of our research has been directed at synthesizing a chromophore that contains functional groups that will chemically incorporate the chromophore into the crosslinking epoxy matrix.

The target chromophore A was chosen for several reasons.



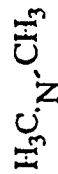
- 1) Substituted azobenzenes with electron donating (dimethylamino) and electron withdrawing (nitro) groups opposite each other are convenient for the laser system used here.
- 2) Aliphatic amine reactive groups were chosen to minimize interaction with the electronic structure of the remainder of the molecule. The presence of an aromatic amine moiety on the same phenyl ring as the nitro group could greatly affect the chromophore's charge transfer ability. The aliphatic nature of the reactive groups is also chemically similar to the amine curing component (believed to be aliphatic).
- 3) Two aliphatic amine groups were chosen so that the chromophore would indeed be polyfunctional and incorporated into the crosslinking matrix as an internal member and not simply as an end member.

The synthetic scheme followed is shown on the attached figure.

- 1) Compounds 1 and 3 are commercially available.
- 2) Compound 2 is prepared from 1 by reaction with thionyl chloride in chloroform to give the substituted benzoyl chloride (not isolated). The acyl chloride was amidated by bubbling ammonia gas through the solution. The amide was recovered and reduced to the benzylamine with lithium aluminum hydride.
- 3) Compound 4 is prepared from 3 by reaction with ice cold nitric acid/sulfuric acid.

- 4) Compound 5 is prepared from 4 by reduction with lithium aluminum hydride in refluxing THF. Yield is approximately 50 percent.
- 5) Compound 6 is prepared by stirring 4 with acetic anhydride in pyridine. The diamide precipitates from solution and may be filtered off and rinsed with ether.
- 6) Nitration of 6 takes place in nitric acid/sulfuric acid at 4 degrees C for 3 hours. Nitration occurs both ortho and para to the acetanilide (NHAc) moiety. This was unexpected as acetanilide is usually a strong para director. Currently we are preparing bulkier diamides using isobutyric anhydride and trimethylacetic anhydride in order to sterically hinder the ortho position.
- 7) Deamidation of the nitrated diamides proceeds with decomposition if performed under basic conditions as shown in the figure. Hydrolysis to the dihydrochloride salt does take place by refluxing in 2N HCl for 12 hours.
- 8) The diazotization and coupling reactions have been attempted using compounds 2 and 5 at pH 2. The product was not purified but the expected change from colorless starting materials to dark red product that was observed (to be expected with this sort of system) strongly suggests that coupling occurred.

2




CONCURRENCE FORM

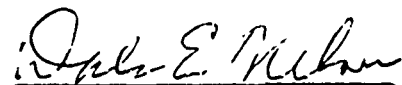
The Avionics Laboratory requests the continuation of the AFOSR fellowship for Mr. Raul Valdes-Perez, studying Adaptive Learning Diagnostics at Carnegie-Mellon University.

Give a brief statement of laboratory and/or Mr Dale Nelson (fellow's mentor) involvement with Mr. raul Valdes-Perez.

Mr Dale E. Nelson met with Mr Valdes-Perez at Carnegie-Mellon University (CMU) in May 1989. At this meeting the direction, scope and progress toward the dissertation was discussed. Mr Valdes-Perez was preparing for the formal presentation of his dissertation proposal and completing the background information search. Mr Valdes-Perez is an intelligent, hard-working, dedicated individual who is making excellent progress toward the completion of his degree. Mr Nelson was able to suggest sources of information which might be of help in the performance of the research.

 14 AUG 1989

MARVIN SPECTOR Date 14 AUG 1989
Director, Avionics Laboratory


Mentor 4 AUG 89
Date

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Raul Valdes-Perez

Semester: Spring 1989

University: Carnegie-Mellon University

Subcontract: S-789-000-018

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

I took no courses this spring; however, I participated in a semester-long seminar on the psychology of scientific reasoning, which is excellent background for my research interests.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

I completed the stage of formally proposing a dissertation this semester. My committee concluded that I should continue along the same tracks; they seemed pleased with the ideas as well as the progress so far.

"I certify that all information stated is correct and complete."

Raul Valdes-Perez
Signature/Fellowship Recipient

Raul Valdes-Perez
TYPED NAME/FELLOWSHIP RECIPIENT

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Raul Valdes-Perez is making satisfactory academic progress toward a Ph.D. in the area of Adaptive Learning Diagnostics in the discipline of Computer Science for the Spring 1989 semester."

Herbert A. Simon
Signature/Advising Professor

Prof. Herbert A. Simon
TYPED NAME/TITLE OF ADVISING
PROFESSOR

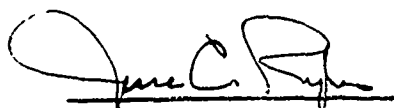
4960C

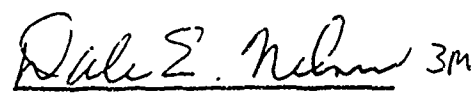
CONCURRENCE FORM

The Avionics Laboratory requests the continuation of the AFOSR fellowship for Mr. Raul Valdes-Perez, studying Adaptive Learning Diagnostics at Carnegie-Mellon University.

Give a brief statement of laboratory and/or Mr. John Camp's (fellow's mentor) involvement with Mr. raul Valdes-Perez.

Mr John Camp has been reassigned from AAAF. He has, therefore, been unavailable to serve as the mentor and Air Force point of contact for Mr Raul Valdes-Perez. The Avionics Laboratory is recommending that Mr Dale E. Nelson, Chief of the Advanced Systems Research Group, WRDC/AAAT-3, be assigned as the mentor. AAAT-3 is responsible for basic research into neural networks, a perfect match for the research that Mr Valdes-Perez is pursuing. Mr Nelson will be at Carnegie-Mellon University for the Industrial Affiliates Review in May and will be in contact with Mr Valdes-Perez at that time to determine the direction and progress of the research.

 26 May 88
Chief Scientist Date

 3M
DALE E. NELSON Date
Mentor

S-789-000-018

NT-62

Rec'd 31 March

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Raul Valdes-Perez

Semester: Fall 1988

University: Carnegie-Mellon University

Subcontract: S-789-000-018

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

I took no courses for credit this semester.

I have already completed all course requirements, and am conducting research toward the dissertation.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

My research concerns the automation of certain inferential tasks carried out by a practicing chemist. The impact of this work on AI will be to elucidate the nature of problems involving experimentation in the real, physical world.

I began the work over the summer, and have been refining the problem and implementing an approach since then. I expect to propose formally a thesis topic next semester.

"I certify that all information stated is correct and complete."

Raul Valdes-Perez

Signature/Fellowship Recipient

Raul Valdes-Perez

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4960C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Raul Valdes-Perez is making satisfactory academic progress toward a Ph.D. in the area of Adaptive Learning Diagnostics in the discipline of Computer Science for the Fall 1988 semester."

Herbert A. Simon
Signature/Advising Professor

HERBERT A. SIMON, PROFESSOR OF COMPS & PSYCHOLOGY
TYPED NAME/TITLE OF ADVISING
PROFESSOR

4960C

CONCURRENCE FORM

The Armstrong Aerospace Medical Laboratory requests the continuation of the AFOSR fellowship for Mr. Richard Volpe, studying Robotics at Carnegie-Mellon University.

Give a brief statement of laboratory and/or Dr. Daniel Repperger (fellow's mentor) involvement with Mr. Ricard Volpe.

Our laboratory and Dr. Daniel W. Repperger have been involved with the research of Mr. Richard Volpe through various interactions. Mr. Volpe has visited our laboratory on two occasions. Once in conjunction with a local Engineering Conference at nearby Wright State University. I have visited Carnegie Mellon about a year ago at Mr. Volpe's Preliminary Exam. I am scheduled to visit in early 1990 for the final exam and an update research summary. Also the advisor of Mr. Volpe, Professor Anand Khosla, visited me twice in the last year. We have discussed Mr. Volpe's research and we communicate every few months through electronic mail (ARPANET) on any new developments.

George Christou 4 DEC 89

Chief Scientist Date

S-789-000-019

Daniel W. Repperger Nov 27

Mentor Date

DANIEL REPPERGER
AAMRL/BBS
WPAFB OH 45433-6573

CONCURRENCE FORM

The Armstrong Aerospace Medical Research Laboratory requests the continuation of the AFOSR fellowship for Mr. Richard A. Volpe, studying Robotics at Carnegie-Mellon University.

Give a brief statement of laboratory and/or Dr. Daniel Repperger's (fellow's mentor) involvement with Mr. Richard A. Volpe.

I have been involved with Mr. Richard Volpe's by participating on his Ph.D. Committee meetings. He has also sent me copies of two recent publications concerning his research. During the last year I have met once with him and twice with his advisor, Dr. Pradeep Khosla at Carnegie-Mellon University.

George Choe 16 Jul 89

Chief Scientist Date

Daniel W. Repperger

Mentor

Date

JUNE
1989

DANIEL REPPERGER
AAMRL/BBS
WPAFB OH 45433-6573

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Richard Volpe

Semester: Summer 1989

University: Carnegie-Mellon University

Subcontract: S-789-000-019

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

please see attached sheet

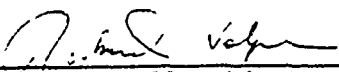
2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

please see attached sheet

3. Give brief statement of your involvement with the Armstrong Aerospace Medical Research Laboratory Laboratory and Dr. Daniel W. Repperger.

please see attached sheet

"I certify that all information stated is correct and complete."



Signature/Fellowship Recipient

Richard Volpe
TYPED NAME/FELLOWSHIP RECIPIENT

Certification of Academic Progress for Richard Volpe

1. Courses: Thesis Research, grade (A).

2. Research:

My research for the summer of 1989 has consisted of initial experimentation with the new DDARM II computer architecture and refinement of the user interface for this architecture.

The initial experimentation was highlighted by the implementation of our superquadric artificial potential scheme. The results of this work were presented at The 5th International Symposium on Robotics Research in Tokyo in August. In summary, we demonstrated the feasibility of our strategy by running resolved acceleration control in conjunction with two superquadric artificial avoidance potentials at a control rate of 200 Hz. Stable and successful goal acquisition and multiple obstacle avoidance was thus achieved.

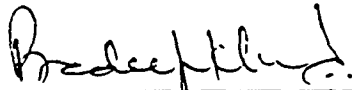
The major advance in the user interface for the system was the inclusion of a six degrees-of-freedom joystick that is now used for controlling the movement of the CMU DDARM II. This provides a mode of control that never before existed for this system. Coupled with the superquadric avoidance potentials, it is now possible to have an operator move the manipulator through the environment while simultaneously preventing it from inadvertent contact with obstacles in the environment.

Work has also begun on the integration of a force sensor into the system.

3. My involvement with Armstrong Aerospace Medical Research Laboratory has been through my affiliation with Dr. Daniel Repperger. Dr. Repperger is a member of my Ph.D. committee and has been associated with my work in this capacity.

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Richard Volpe is making satisfactory academic progress toward a Ph.D. in the area of Robotics in the discipline of Applied Physics for the Summer 1989 semester."



Signature/Advising Professor

Pradeep Khosla

TYPED NAME/TITLE OF ADVISING
PROFESSOR

2094t

CONCURRENCE FORM

The Armstrong Aerospace Medical Research Laboratory requests the continuation of the AFOSR fellowship for Mr. Richard A. Volpe, studying Robotics at Carnegie-Mellon University.

Give a brief statement of laboratory and/or Dr. Daniel Repperger's (fellow's mentor) involvement with Mr. Richard A. Volpe.

Dr. Daniel W. Repperger served on the Preliminary Doctoral Exam (PRELIM Exam) held at Carnegie-Mellon University about 18 months ago. He spent the day with Mr. Volpe. About 9 months ago, Mr. Volpe visited Wright Patterson Air Force base for about 2 days. We had a number of discussions with the Robotics people in AAMRL/BBM and AAMRL/BBA.

Also in the last 2 years, I have met with Mr. Volpe at two conferences where he presented papers. We had subsequent discussions on the material he presented at the conferences and how they related to our laboratory effort.

A trip back to Carnegie-Mellon is scheduled within the next 6 months for an updated progress report.

S. E. Welch 30 April 79

Chief Scientist

Date

Dr. D. W. Repperger April 17,

Mentor

Date

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Richard Volpe

Semester: Spring 1989

University: Carnegie-Mellon University

Subcontract: S-789-000-019

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

please see attached sheet.


2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

please see attached sheet

3. Give brief statement of your involvement with the Armstrong Aerospace Medical Research Laboratory Laboratory and Dr. Daniel W. Repperger.

please see attached sheet

"I certify that all information stated is correct and complete."



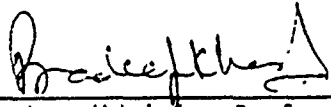
Signature/Fellowship Recipient

Richard Volpe
TYPED NAME/FELLOWSHIP RECIPIENT

2094t

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Richard Volpe is making satisfactory academic progress toward a Ph.D. in the area of Robotics in the discipline of Applied Physics for the Spring 1989 semester."

A handwritten signature in cursive script, appearing to read 'Pradeep Khosla', written over a horizontal line.

Signature/Advising Professor

Pradeep Khosla

TYPED NAME/TITLE OF ADVISING
PROFESSOR

2094t

Certification of Academic Progress for Richard Volpe

1. Courses: Thesis Research, grade (A).

2. Research:

My research for the spring of 1988 has mainly consisted of participation in the construction a new computer architecture for the CMU DDARM II. Previously it became apparent to us that modification of the control architecture was desirable due to the complexity of the control algorithms we have tested and the limitations of our old computer hardware. The goals have been an improvement in the real-time performance and the flexibility and ease of use of the system. The new system has been constructed, most of the software has been written, and testing and debugging is currently taking place.

The following control schemes are currently available with the new system: stiffness control, damping control, dynamics compensation, impedance control, explicit force control, and obstacle avoidance using artificial potentials. Others may be easily added under the new design. Experimentation and data collection/analysis are planned for the immediate future.

3. My involvement with Armstrong Aerospace Medical Research Laboratory has been through my affiliation with Dr. Daniel Repperger. Dr. Repperger is a member of my Ph.D. committee and has been associated with my work in this capacity.

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Richard Volpe

Semester: Fall 1988

University: Carnegie-Mellon University

Subcontract: S-789-000-019

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Please see attached sheet.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Please see attached sheet.

3. Give brief statement of your involvement with the Armstrong Aerospace Medical Research Laboratory Laboratory and Dr. Daniel W. Repperger.

Please see attached sheet.

"I certify that all information stated is correct and complete."


Signature/Fellowship Recipient

Richard Volpe
TYPED NAME/FELLOWSHIP RECIPIENT

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Richard Volpe

Semester: Fall 1988

University: Carnegie-Mellon University

Subcontract: S-789-000-019

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Please see attached sheet.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Please see attached sheet.

3. Give brief statement of your involvement with the Armstrong Aerospace Medical Research Laboratory Laboratory and Dr. Daniel W. Repperger.

Please see attached sheet.

"I certify that all information stated is correct and complete."


Signature/Fellowship Recipient

Richard Volpe
TYPED NAME/FELLOWSHIP RECIPIENT

Certification of Academic Progress for Richard Volpe

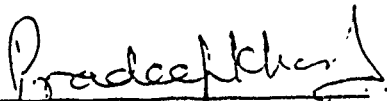
1. Courses: Thesis Research, grade (A).

2. Research: My research for the fall of 1988 consisted of two major goals: initial implementation of, and experimentation with, various hybrid control schemes on the DDARMII; and participation in the implementation of tactile sensing for the DDARMII. The control schemes implemented were various forms of hybrid position/force control in Cartesian space. Among these were algorithms for stiffness control, damping control, dynamics compensation, impedance control, explicit force control, and obstacle avoidance using artificial potentials. These algorithms provided initial experimental data on their viability, and enabled the implementation of tactile sensing capabilities by a colleague and myself. (A copy of the paper detailing this work is included.) However, it became apparent to us that due to the complexity of the control algorithms tested and the limitations of our computer hardware, that modification of the control architecture was desirable. Therefore, we set out to design a new architecture. The goal is not only an improvement in real-time performance, but also an improvement in the flexibility and ease of use of the system. This work has continued into the spring.

3. My involvement with Armstrong Aerospace Medical Research Laboratory has been through my affiliation with Dr. Daniel Repperger. Dr. Repperger is a member of my Ph.D committee and has been associated with my work in this capacity.

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Richard Volpe is making satisfactory academic progress toward a Ph.D. in the area of Robotics in the discipline of Applied Physics for the Fall 1988 semester."

A handwritten signature in dark ink, appearing to read "Pradeep Khosla", written over a horizontal line.

Signature/Advising Professor

Pradeep Khosla

TYPED NAME/TITLE OF ADVISING
PROFESSOR

2094t

Real-Time Edge Tracking Using a Tactile Sensor

Alan D. Berger, Richard Volpe and Pradeep K. Khosla

Department of Electrical and Computer Engineering

The Robotics Institute

Carnegie-Mellon University

Pittsburgh, PA 15213

Abstract

Object recognition through the use of input from multiple sensors is an important aspect of an autonomous manipulation system. In tactile object recognition, it is necessary to determine the location and orientation of object edges and surfaces. We propose a controller that utilizes a tactile sensor in the feedback loop of a manipulator to track along edges. In our control system, the data from the tactile sensor is first processed to find edges. The parameters of these edges are then used to generate a control signal to a hybrid controller. In this paper, we present theory for tactile edge detection, and an edge tracking controller. In addition, experimental verification of the edge tracking controller is presented.

1. Introduction

Object recognition is an important problem in robotics [18], particularly for autonomous manipulation systems. In the most general form, it is the problem of determining the environment from sensory data. The long-term goal of our research is to address the issue of object recognition using tactile data through the process of exploring the environment by moving the sensor. We call this approach dynamic object exploration.

Dynamic object exploration involves scheduling moves of the manipulator based on previously acquired data in order to create a more complete description of the object that is being explored. Thus, there is an interaction between manipulation and sensing. In dynamic exploration, the scheduled move affects the data obtained from the sensor, which in turn affects the next move of the manipulator. The two main steps in dynamic object exploration are: first to create strategies for scheduling manipulator moves; and second, to develop processing algorithms that will extract features of interest from the currently available data.

Researchers have actively addressed issues in both of the above mentioned components of dynamic object exploration and especially so in the context of using tactile data for exploration. Early work in edge and surface tracking was done by Bajcsy [2]. In this work, the utility of using a tactile sensor to move about an object to detect features is discussed. Work in object recognition has been done by Allen [1], Dario, et al [7], Ellis [8], Grimson [10], Klatzky, et al [12], Schneiter [19], and Stansfield [20]. Some of these groups [7, 12] take the approach of creating tactile subroutines to find particular features of an object. In this approach, a feature is extracted by calling a specific subroutine that moves and takes the appropriate measurements with the sensor. Other groups have taken a completely different approach to object recognition [8, 10, 19]. They have devised algorithms that determine the best path to approach a planar polygonal object such that it can be identified in a small number of discrete moves of the sensor.

The area of tactile image processing has received less attention than object exploration. Work has

proceeded in both pattern recognition [14], and edge finding [16, 9]. Muthukrishnan, et al [16] developed a vision-like algorithm to detect edges in a tactile image. In contrast, Fearing and Binford [9] use the impulse response of their sensor to process the signals to measure the curvature of an object.

At Carnegie Mellon, our research group is addressing multi-sensor based manipulation. The goal of our research is to incorporate position, velocity, force, vision, and tactile sensors in the real-time feedback loop to create an autonomous manipulator system. The focus of this paper is to describe the use of a tactile sensor in the real-time feedback loop for edge tracking. We call this system a dynamic edge extractor. Our methodology utilizes a tactile sensor mounted on the end-effector of a manipulator to obtain data about objects. This system consists of both signal processing and control aspects. The role of the signal processing module is to find edges in the data from the tactile sensor, while the control module generates signals to servo the center of the tactile sensor along the edge. In this paper, we present the theory behind our signal processing and control modules in addition to the results of an experimental verification of the dynamic edge extractor using the CMU Direct Drive Arm II and a Lord LTS-210 Tactile Array Sensor.

2. Signal Processing

In this section, we present a brief description of the signal processing required to detect edges in a tactile image. Further details are presented in [3]. We propose algorithms that are based on the physical properties of the tactile sensor. The important characteristics of our sensor, a Lord LTS-210, are that it has low spatial resolution and exhibits mechanical cross-talk noise. The noise is due to mechanical coupling generated by the rubber covering on the sensor. In addition, the background tactile elements (taxels) have non-zero force readings due only to mechanical cross-talk. Thus, assuming there is no cross-talk, edges are present at the locations where measured force goes from non-zero to zero. Taking these properties into account, we have devised an edge detecting algorithm that consists of two steps. The first step is an adaptive thresholder to remove cross-talk noise, and the second consists of an edge detector.

2.1. Adaptive Thresholder

The purpose of this filtering stage in our algorithm is to remove the effects of cross-talk noise from the tactile image. This operation simplifies the process of detecting edges because with no cross-talk noise, the locations where the force goes from a non-zero value to zero indicate the edges of planar surfaces. As will be discussed in the following section, the edge detector does not utilize the magnitudes of the taxels. It only uses the state of each taxel, whether it is zero or non-zero. Thus the filter may distort magnitude without adverse side effects. In the ensuing discussion of the thresholding algorithm, we show how this property is utilized.

Tactile images are very noisy. However, the noise of concern exists only at the edges of objects. In particular, the noise causes taxels that should read a force of zero to have a non-zero value. These taxels always have values that are less than their neighbors which are directly beneath the object. Hence, a thresholder that can choose the appropriate threshold at each taxel may be used to remove the noise. The threshold value is determined by the neighbors of the current taxel, thus making the thresholding an adaptive procedure. The proposed algorithm consists of three basic steps:

1. At each pixel, the force value at each of the four-connected neighbors is checked.
2. If any of these neighbors are large enough to have caused the current pixel to be noise (greater than threshold), the current pixel is set to 0 (no force).
3. Otherwise the pixel is set to a constant.

The threshold for a given taxel value is the minimum value that a neighbor must have in order for the original taxel to be cross-talk. Thus, if all neighbors of a taxel are below threshold, the taxel is considered to be part of the signal. Threshold values are determined through an experimental procedure which is described in [3]. Thresholds obtained with our sensor are summarized in Table 2-1. In this table, the first column is the cross-talk value, and the second column is the smallest value that will cause that cross-talk value.

Cross Talk	Minimum Neighbor
2	4
4	10
6	20

Table 2-1: Filter Threshold Values

2.2. Edge Detector

Edge detection in the thresholded tactile image is accomplished very efficiently. This is largely due to the assumption that the measured force goes to zero on one side of an edge, and is some non-zero value on the other side of the edge. Since the thresholding step filters out the taxels that have non-zero readings purely due to cross-talk, all that remains for the edge detector to do is to find those taxels that are neighbors of taxels with zero values.

Our edge detection algorithm consists of the following steps:

1. For each taxel, the eight-connected neighbors are checked.
2. If at least one of these neighbors is 0, the current taxel is copied to the edge image.
3. Otherwise the corresponding taxel in the edge image is set to 0.

This algorithm is very fast and minimally distorts the size, shape and position of the object. What does not come out of the algorithm is an estimate of the slope of the edges. Vision researchers have recognized that slope provides a considerable amount of information about the edge [6, 16]. However, since tactile images are small, they are simple in structure, and simply finding the position of edges appears to be sufficient for higher-level processing. In addition, standard vision edge operators that do provide this information have a number of undesirable characteristics for taction, such as edge spreading and high computational requirements. The slope of object edges may be obtained by combining the tactile and position information as the sensor tracks along the edge of an object.

3. Control

In this section, we discuss the control aspects of dynamic edge extraction [4]. The edge tracker starts on an edge and uses the extracted parameters of the edge to generate control signals to move along that edge. The control scheme is hierarchical, with the tactile controller wrapped around a cartesian space hybrid controller. In the ensuing paragraphs, we describe both the hybrid controller used in our scheme and the tactile controller.

3.1. Hybrid Controller

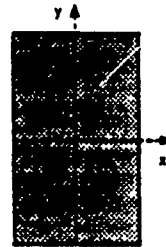


Figure 3-1: Sensor Coordinate Frame

Hybrid force and position control provides the ability to control both forces on the end effector and position of the sensor, [17]. Figure 3-1 depicts the sensor frame coordinate axis. The shaded box shows the face of the sensor. The x and y axis lie in the plane of the sensor, and the z axis (not shown) points out of the page. For tactile sensing, we control the normal force, and torques about the x and y axis of the sensor. Position is controlled in the xy plane, and about the z axis of the sensor. Normal force control is necessary to ensure that the tactile data is within the middle of the operating range [3]. High forces change the sensor cross-talk characteristics, and low forces result in a very low signal to noise ratio. Controlling torques about the x and y axis of the sensor allows tracking of surfaces that are not flat. Specifically, the desired torques are set to zero in order to place the sensor as flush as possible against the surface. Position control in the plane of the sensor is used because the processed sensor data provides information about the surface in the xy plane of the sensor. Thus, it is in this plane that we generate position control signals. Further, we control rotation about the z axis of the sensor. In summary, the hybrid controller commands position/orientation in three degrees of freedom, and commands force/torque in the other three. The x and y positions, and the rotation about the z axis of the end effector are controlled. Torques about the x and y axis, and force along the z axis are controlled.

3.2. Edge Tracking Controller

The edge tracking controller utilizes the edges extracted from tactile images to generate new reference signals for the hybrid arm controller. Edge tracking is initiated by positioning the tactile sensor on an edge. Through the edge detection technique discussed in the preceding section and the Modified Adaptive Hough Transform (MAHT) [5], our implementation of the Hough Transform, the tracker finds the parameters of the edge. The tracker queries a higher level process to determine which direction to travel, and begins to move the end effector in that direction. After this startup, the edge tracker functions independently of higher level input, utilizing a weighted least squares line fit to the data to determine the current parameters of the line. The Hough Transform is also performed every cycle to determine if any

new edges have become visible. Each time through the loop, the robot's reference position is set to be the end point of the line segment on the sensor. Thus, if the edge extends past the end of the sensor, the point where the line intersects the edge of the sensor is selected as the goal point. As the end of a edge becomes visible to the sensor, the reference position is set to the actual end of the edge. In addition, a reference velocity is set such that the end effector should arrive at the reference position at the same time that a new reference position is generated.

The *Estimate Force* box computes a reference force such that the taxels operate in the middle of their range. Specifically, it takes the thresholded image and counts the number of taxels that are non-zero. The number of non-zero taxels multiplied by the area of each taxel is an estimate of the area of the sensor that is covered by objects. A desired normal force to the sensor may then be generated by dividing the full scale force by the area in contact with the surface. Full scale force is the total force to drive all taxels to mid-range when the entire sensor is on a flat surface.

Now, we return to the output of the adaptive thresholder. The thresholded image is passed through the edge detector (discussed in Section 2) and the result is sent to a weighted least squares line parameter estimator. This algorithm is used to estimate the slope and intercept of the edge based on the slope and intercept computed in the previous cycle. All data points in the image are weighted with a gaussian function, with $\sigma = 0.75$. A standard deviation of 0.75 was determined from our experimental work to be the best compromise for both accurate line fitting and adapting of line parameters. The weighting function is oriented such that data points located on the predicted location of the line have the highest weight. As the perpendicular distance of a point to the predicted line increases, the weight of that point decreases.

Use of this weighting function allows us to pass all of the data points to the line fitting algorithm without pre-processing to remove points that don't appear to be on the line. After the slope and intercept parameters for the edge are determined, the data points in the image corresponding to that line are removed. Also, the end points of the line are determined at this stage. These computations are the same as those performed by the MAHT, the details of which are discussed in [5]. The point removal and end point computation are part of the *Weighted Least Squares* box in the block diagram.

The weighted least squares computation requires an estimate of the parameters of the previous line segment in the current frame. The *Predict Line Parameters* box in the diagram performs this operation. The end effector will have translated and possibly rotated since the previous set of line parameters were determined. Thus the slope and intercept stored from the previous cycle must be updated to reflect this change. The predictor calculates the parameters of the current line based on the parameters of the previous line, the position of the end effector in the previous cycle, and the current position.

The remaining image is passed on to the Modified Adaptive Hough Transform. The MAHT extracts multiple lines of arbitrary slope from low signal to noise input data. Any line segments other than the one being currently tracked will be detected by this algorithm. If there are no edges remaining in the image, the transform exits, and the parameters and end points determined by weighted least squares are passed through the *Selector*. If there are new line segments, the higher level process will be informed. At this point a new line segment may be selected for tracking. When a new segment is selected, the *Selector* passes the parameters determined by MAHT to the predictor, and the end points determined by MAHT to the *Choose Goal Point* process.

Finally, *Choose Goal Point* determines which of the two end points of the segment should be set as the new reference position for the robot. The choice is made such that the robot continues to move in the same direction that it has been moving. The reference velocity is set to the distance to the new goal position divided by the edge tracking sampling period.

3.3. Discussion

The design of the edge tracking controller has several desirable properties. Specifically, it handles the ends of segments smoothly, it can track curves in addition to straight lines, and the design is tolerant of any size sensor and data rate. In the following paragraphs, we discuss each of these points in some detail.

As the tactile sensor approaches the end of a line segment, the controller slows the arm down. When the center of the sensor reaches the end point, the arm stops. This action is a natural consequence of the way that new reference points for the hybrid controller are generated. In each cycle, the visible end of the line segment is chosen as the new reference point. Hence, before the end of the line is under the sensor, the point where the line leaves the sensor is the reference point. However, as the end point becomes visible, the controller chooses that point as the goal. This new goal point is closer to the center of the sensor than the edge of the sensor, and as a result, the velocity of the arm decreases. As the center of the sensor gets closer to the end of the segment, the arm continues to slow down, until it stops when the segment end is below the center of the sensor. This allows the arm to accurately position itself at the end of the segment, and provides an easy way to detect the end of a line segment.

Gradual curves appear as piecewise straight lines to the tactile sensor, allowing it to track them. In

each cycle, new line parameters are fit to the segment of the curve that is under the sensor by the weighted least squares method. The parameters that control the weighting are the line parameters from the previous cycle. The old parameters will not be correct, as both the slope and intercept of the new section of the curve may be different. However, the old values are close enough to the correct ones that the weighting function will still be in approximately the correct location, and weighted least squares will extract the correct new parameters. Thus, the procedure of adapting the line parameters each cycle allows the system to track curves in addition to straight lines.

The sampling rate of the sensor only affects the maximum tracking velocity. As discussed above, the reference point for the hybrid controller is set to the intersection of the line with the edge of the sensor. Further, the reference velocity is set to the length of the new reference trajectory divided by the cycle time of the controller, T . As the sampling rate of the sensor decreases, T increases. Thus, desired velocities are reduced, and the reference points are placed closer together. In this scheme, there is no danger of the manipulator traveling faster than new data arrives.

4. Experimental Apparatus

In this section, we describe the hardware used in our laboratory to implement the tactile edge follower. The hardware consists of the CMU DD Arm II, control computers, a Lord Force/Torque sensor, and a Lord LTS 210 Tactile Array Sensor. The tactile control software is run on a Sun 3 computer.

4.1. Control Computers

The hardware of the DD Arm II control system consists of four integral components: the Sun workstation, the Motorola M68000 microcomputer, the Marincos processors and the TMS-320 microprocessor-based individual joint controllers. All of the computers, with the exception of the Sun are connected through a common Multibus backplane. The Eurocard Sun 3 is connected to the backplane through a serial line and interface card, operating at 4800 Baud. A simple packet based communications scheme between the M68000 Coordinating Processor and the Sun operates over this serial connection.

Previous control work included the development of the customized Newton-Euler equations for the CMU DD Arm II which achieved a computation time of 1 ms on the Marincos processor. The details of the customized algorithm, hardware configuration and the numerical values of the dynamics parameters are presented in [11]. For tactile sensing, we run a cartesian position controller on one of the Marincos boards, while gravity compensation torques are computed on the other Marincos. The edge tracking controller runs on the Sun. Each cycle, new reference positions are sent from the Sun to the 68000, and the current position is transmitted from the 68000 to the Sun.

4.2. Lord LTS 210 Tactile Array Sensor

To perform our traction experiments, we added a Lord LTS-210 tactile array sensor to the DD Arm II system. This sensor is mounted at the end-effector of the robot. The sensor is an array of 10×16 elements spaced on 1.8mm centers [13]. Each sensing site is a small plunger mounted such that as it is depressed, it blocks the light path between a LED and a photodiode [15]. Sixteen different increments in deflection may be read for each site in the sensor. A sheet of rubber protects the top surface of the sensor, but also mechanically couples the sensing sites. The sensor is interfaced to the Sun 3 through a 9600 Baud serial line.

5. Experimental Results with the CMU Direct Drive Arm II

In the ensuing paragraphs, we present the results of two different edge tracking experiments along with some observations about the use of a tactile sensor for edge tracking. First, we discuss a change in the thresholds used by the adaptive thresholder, and our strategy for orienting the tactile sensor for edge tracking. Then, we show the trajectory followed by the manipulator while tracking both straight and curved edges. The straight edge experiment allows us to view the accuracy of the tracking system, while the curved edge experiment shows the line parameter adaptation capability.

5.1. Observations

Our experiments to determine the threshold values for the adaptive thresholder show that taxel values of 2 are noise if there is a four connected neighbor of value 4 or greater [3]. During early edge tracking experiments, however, we found that after the sensor is moved over a surface for a distance of a few centimeters random 2's appear in the image. Thus, motion of the sensor against a surface makes force values of 2 unreliable. To compensate for this phenomena, the adaptive thresholder parameters were adjusted to always filter out twos regardless of the force on neighbors. No side effects in system capability are produced by the elimination of 2 as a usable force value. As discussed in Section 3, forces on the sensor are maintained above 2 for best utilization of the sensor.

We track edges with the sensor oriented such that it only contacts the edge, and not the surfaces of the object. Although the algorithms presented in the previous sections are general and may be used to track edges with the sensor in contact with the surface, we found that the friction between the object and the sensor is very high when the system is used in this mode. With our approach, two effects combine to reduce the friction. First, less area is in contact with the surface since the sensor is only contacting a line, instead of a plane. Second, a lower normal force is required. The normal force necessary to operate the sensor in the mid-region is proportional to the area of the sensor in contact with the surface. Each taxel in contact with the surface must experience a force large enough to keep it in operating range. Thus the normal force that must be exerted by the manipulator is approximately the product of the force each taxel requires and the number of active taxels. Lower forces on the sensor not only help to reduce the requirements placed on the manipulator, but also reduce wear on the sensor.

5.2. Edge Tracking

Figure 5-1 shows the result of tracking a straight edge on a metal box. In each cycle, the position of the end effector was recorded. Dots in the graph correspond to these end effector positions. Thus, the graph shows the distance between samples in addition to the robot's trajectory. The dashed line in the figure is an approximation of the location of the actual edge and is included for reference. This reference line is nearly indistinguishable from the robot's trajectory. In this experiment, the tactile sensor was oriented such that the long dimension (the 16 rows) was parallel to the direction of travel. The end effector traced a path starting at (0.47, 0.1) and ending at (0.72, 0.26), with an average speed of 5 mm/sec.

The plot (Figure 5-1) shows the typical characteristics of our edge tracking system. First, we note that its accuracy is acceptable and the errors are within the width of the lines in this plot. The position errors are approximately 1mm. Remember that the tactile sensor resolution is 1.8mm, and the reference line is only an approximation to the actual edge. Thus, we conclude that the position error is well within expectations for the system.

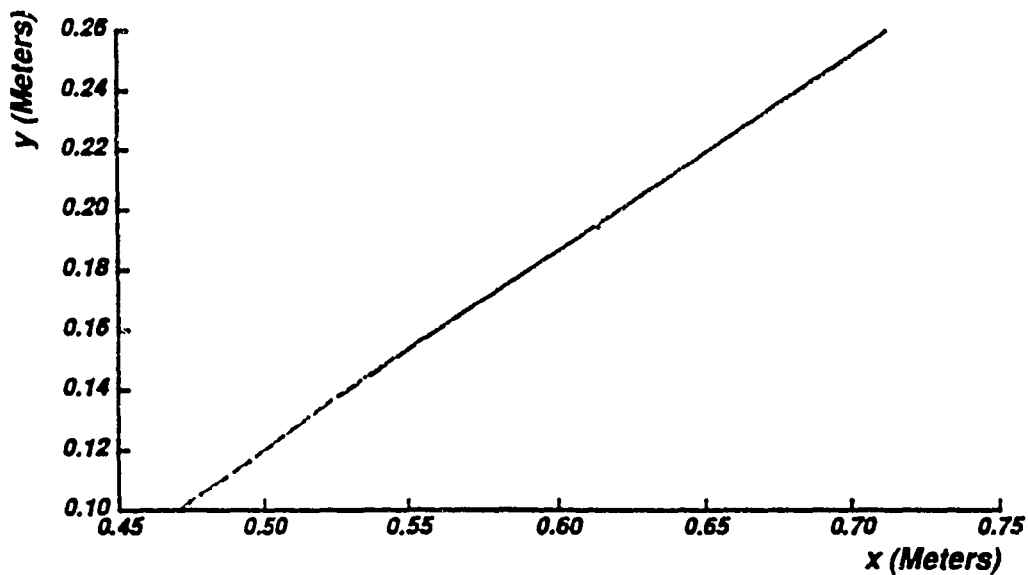


Figure 5-1: Straight Edge Tracking

Now we discuss the start and end points. At the start, (0.47, 0.1), the velocity does not appear to be as consistent as the during the remainder of the trajectory. This is to be expected as the end effector moves to place the center of the tactile array on the line, and the estimated line parameters adapt to the edge. Further, at the beginning of the line the manipulator is at rest. Thus, the first move request is a step input to the cartesian controller. Our current controller is somewhat under-damped and requires time to reach steady motion. On this particular run, the motion of the sensor smoothed out after 4 or 5 cm. At the very end of the trajectory, the dots become close together, indicating that the end effector slowed down. This is precisely the action designed into the system. The visible end of the line segment is always chosen as the new goal point. Thus, as the end of an edge comes into view, the commanded trajectory length, and end effector velocity decreases.

The next experiment involved tracking a S shaped object. Figure 5-2 shows the results when the sensor is started with the long dimension approximately oriented at a positive 45 degree angle to the x axis. Tracking follows a smooth arc beginning at (0.45, -0.14) and ending at (0.93, 0.21). The primary result from this experiment is the verification of the line parameter adaptation. The edge tracker always attempts to follow a straight line. Curves are taken to be piecewise linear, with line parameters changing slightly each cycle. The motion shown in Figure 5-2 clearly shows that line parameters are adapting properly. As with the straight line, we note a small amount of oscillation at the beginning of the trajectory, and a decrease in velocity at the end.

6. Summary

This paper presents the utilization of a tactile sensor in the feedback loop of a robot controller. There are two main components to our dynamic edge tracker: tactile signal processing and control. We base our tactile signal processing algorithms on the physical properties of the sensor. Thus, we accomplish edge detection by a two step process that first filters mechanical cross-talk noise and second finds edges by looking for transitions from non-zero to zero force. The controller uses detected line segments to generate reference signals for a manipulator. During each cycle of the edge tracker, the estimated

- [7] P. Dario, M. Bergamasco, D. Femi, A. Fiorillo, A. Vaccarelli.
Tactile Perception in Unstructured Environments: A Case Study for Rehabilitative Robotics Applications.
Proc IEEE Conf on Robotics and Automation 3:2047 - 2054, 1987.
- [8] R.E. Ellis.
Acquiring Tactile Data for the Recognition of Planar Objects.
Proc IEEE Conf on robotics and Automation 3:1799 - 1805, 1987.
- [9] R.S. Fearing, and T.O. Biford.
Using a Cylindrical Tactile Sensor for Determining Curvature.
Proc IEEE Conf on Robotics and Automation :765 - 771, 1988.
- [10] W.E.L. Grimson, and T. Lozano-Perez.
Model-Based Recognition and Localization from Tactile Data.
Proc IEEE Conf on Robotics and Automation :248 - 255, 1984.
- [11] P.K. Khosla and T. Kanade.
Experimental Evaluation of the Feedforward Compensation and Computed-Torque Control Schemes.
In Stear, E. B. (editor), *Proceedings of the 1986 ACC*. AAAC, Seattle, WA, June 18-20, 1986.
- [12] R.L. Klatzky, R. Bajcsy, and S.J. Lederman.
Object Exploration in One and Two Fingered Robots.
Proc IEEE Conf on Robotics and Automation 3:1806 - 1809, 1987.
- [13] Lord LTS-210 Tactile Sensor.
Installation and Operations Manual.
Lord Corp., Cary, North Carolina, 1987.
- [14] R.C. Lou, and Tsai.
Object Recognition using Tactile Image Array Sensors.
Proc IEEE Conf on Robotics and Automation :1248 - 1253, 1986.
- [15] G.A. McAlpine.
Tactile Sensing.
Sensors :7 - 16, April, 1986.
- [16] C. Muthukrishnan, D. Smith, D. Myers, J. Rebman, and A. Koivo.
Edge Detection In Tactile Images.
Proc. IEEE Conf. on Robotics and Automation 3:1500 - 1505, April, 1987.
- [17] M.H. Raibert and J.J. Craig.
Hybrid Position/Force Control of Manipulators.
J. Dynamic Systems, Measurement, Control , 1981.
- [18] A.A.G. Requicha.
Representations for Rigid Solids: Theory, Methods, and Systems.
ACM Computing Surveys 12(4):437 - 464, December, 1980.
- [19] J.L. Schreiner.
An Objective Tactile Sensing Strategy for Object Recognition and Localization.
Proc. IEEE Int'l Conf. on Robotics and Automation :1262-1267, April, 1986.
- [20] S.A. Stansfield.
Primitives, Features, and Exploratory Procedures: Building a Robot Tactile Perception System
Proc IEEE Conf on Robotics and Automation 2:1274 - 1279, 1986.

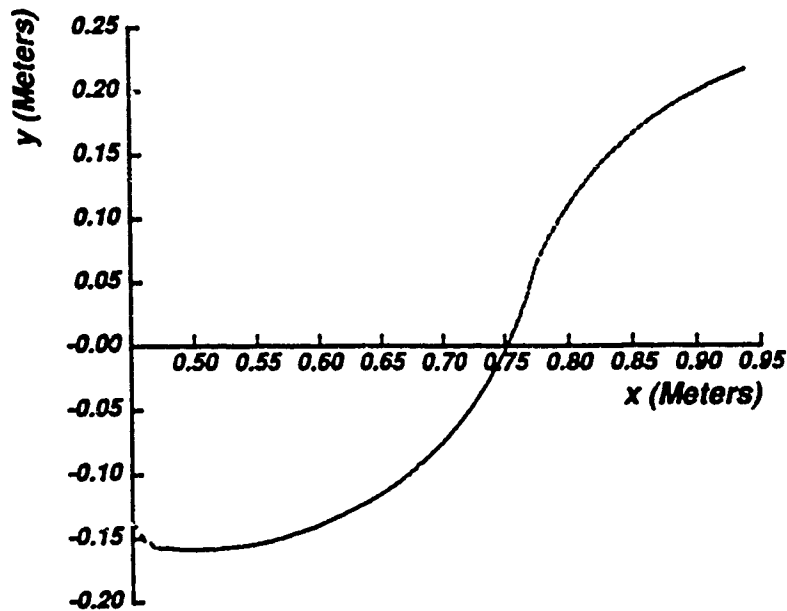


Figure 5-2: S Curve Tracking

parameters of the line are transformed to the current frame. These parameters are used to position a weighting function for a weighted least squares estimate of the new line. Performing this procedure every time through the control loop allows the line parameters to continuously adapt. Continuous adaptation of the parameters, in turn, allows the system to track curved objects in addition to straight objects.

References

- [1] P. Allen.
Surface Descriptions from Vision and Touch.
Proc IEEE Conf on Robotics and Automation :394 - 397, 1984.
- [2] R. Bajcsy.
What can we learn from one finger experiments?
In M. Brady and R. Paul (editor), *The First International Symposium on Robotics Research*. MIT Press, Cambridge, MA, 1984.
- [3] A.D. Berger, and P.K. Khosla.
Edge Detection for Tactile Sensing.
Proc. SPIE's Cambridge Symposium on Optical and Optoelectronic Engineering: Advances in Intelligent Robotics Systems, November, 1988.
- [4] A.D. Berger and P.K. Khosla.
Real-Time Feature Tracking Using a Tactile Sensor.
Technical Report, Departement of Electrical and Computer Engineering, Dec, 1988.
- [5] A.D. Berger, and P.K. Khosla.
The Modified Adaptive Hough Transform (MAHT).
Technical Report, Dept. of Electrical and Computer Engineering, Carnegie Mellon University, 1988.
- [6] J.B. Burns, A.R. Hanson, and E.M. Riseman.
Extracting Straight Lines.
IEEE Trans. on Pattern Analysis and Machine Intelligence 8(4):425 - 455, July, 1986.

CONCURRENCE FORM

The Rome Air Development Center requests the continuation of the AFOSR fellowship for Mr. Randall P. Pope, studying Distributed Processing at Clarkson University.

Give a brief statement of laboratory and/or Mr. Richard Metzger's (fellow's mentor) involvement with Mr. Randall P. Pope.

Mr. Metzger has periodically reviewed Mr. Pope's progress. Mr. Pope has completed all but one course and is finalizing plans for his dissertation research. He has completed one technical paper and is preparing a second paper. He is scheduled to visit RADC on 26 July 1989 to lead a seminar on his current work.

Fred J. Diamond
Chief Scientist Date

Richard A. Metzger 6/27
Mentor Date

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Randall P. Pope

Semester: Spring 1989

University: Clarkson University

Subcontract: S-789-000-020

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Course No.	Description	Grade	Credit Hours
MA542	Theory of Computation	A	3
EE511	Advanced Topics in AI	A	3
ES610	ECE-Seminar	Pass	1
ES613	Thesis	N/A	5
			<hr/> 12

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

I have conducted a literature search of papers in the field of planning. This survey covered the classical planning systems through the present work in the field. This search will become a part of my Ph.D. proposal. I have also begun the implementation of the negotiation phase of the distributed planner being developed at Clarkson.

"I certify that all information stated is correct and complete."


Signature/Fellowship Recipient

Randall Pope

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4963C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Randall P. Pope is making satisfactory academic progress toward a Ph.D. in the area of Distributed Processing in the discipline of Artificial Intelligence for the Spring 1989 semester."

Robert C. Meyer
Signature/Advising Professor

Robert C. Meyer
TYPED NAME/TITLE OF ADVISING
PROFESSOR

4963C

CONCURRENCE FORM

The Rome Air Development Center requests the continuation of the AFOSR fellowship for Mr. Randall P. Pope, studying Distributed Processing at Clarkson University.

Give a brief statement of laboratory and/or Mr. Richard Metzger's (fellow's mentor) involvement with Mr. Randall P. Pope.

Mr. Metzger has received and reviewed a copy of Mr. Pope's master thesis. In addition, he has discussed Mr. Pope's progress with him and with Professor Meyer during the past six months.

Fred Beaman 2- Feb 89

Chief Scientist Date

Richard Metzger 27 Feb 89

Mentor Date

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Randall P. Pope

Semester: Fall 1988

University: Clarkson University

Subcontract: S-789-000-020

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Course	Grade	Credit Hours
Digital System Design	A	3
Introduction to Robotics	A	3
Seminar	Pass	1
Thesis Credit	Pass	5

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

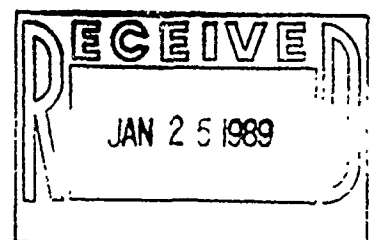
During the fall semester, I completed the requirements for my master's degree. I defended my thesis on September 8 and it was accepted by the thesis committee. A copy of my thesis is enclosed. In addition, I took the Ph.D. Induction exam at Clarkson and I have been notified that I passed.

"I certify that all information stated is correct and complete."


Signature/Fellowship Recipient

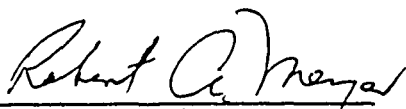
Randall P. Pope
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4963C



CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Randall P. Pope is making satisfactory academic progress toward a Ph.D. in the area of Distributed Processing in the discipline of Artificial Intelligence for the Fall 1988 semester."



Signature/Advising Professor

Robert A. Meyer

TYPED NAME/TITLE OF ADVISING
PROFESSOR

4963C

CLARKSON UNIVERSITY

Role Recognition in
Multiagent Distributed Planning

A Thesis
by
Randall P. Pope

Department of Electrical and Computer Engineering
(Systems Engineering)

Submitted in partial fulfillment of the requirements
for the degree of
Master of Science
(Electrical Engineering)

September 8, 1988

Accepted by the Graduate School

DATE

DEAN

The undersigned have examined the thesis entitled "Role Recognition in Multi-agent Distributed Planning" presented by Randall P. Pope, a candidate for the degree of Master of Science, and hereby certify that it is worthy of acceptance.

4-23-88

DATE

Robert C. Meyer

ADVISOR - Dr. Robert Meyer

Susan E. Conry

Dr. Susan Conry

Mark Koch

Dr. Mark Koch

Abstract

Distributed resource allocation is a problem of concern in many domains such as retail merchandise distribution, military operations, and corporate management to name a few. This thesis presents a *distributed* planner which extends the current work in planning by designating certain objects as resources so that they may be efficiently allocated for effective use in multiple goals. The planner consists of two stages, plan generation and multistage negotiation. The plan generation phase is the focus of the work presented. During plan generation, agents are required to generate plans which utilize limited system resources in domains where both the knowledge about resources and the control over these resources are distributed among the agents. As a result, plan decomposition is dynamic and diffuse in nature. To effectively plan using such decompositions, each agent must be capable of determining its role in multiple plan decompositions with only a partial view of the associated global plans. *Support names* are introduced as a means to allow each agent to recognize which sets of local actions are required by various plan decompositions for the same goal. The use of support names has been implemented in a system which generates plans for the restoral of service in a communications network. Results from experimentation are presented which show that plan generation in this class of problems can be accomplished by sending a limited amount of information between agents. It is unnecessary for any single agent to acquire complete global information about the system.

Acknowledgements

At this time I wish to thank my advisor, Dr. Robert Meyer. It is his ability to mix the personal and professional sides of life that has encouraged me in the pursuit of my degree. I thank him for his guidance. I also wish to thank Marty Q. Humphrey for his insights during long design discussions in the lab. I thank Doug MacIntosh for creating a flexible simulation tool which greatly simplified experimentation, and for providing all the "Hey Doug, can we have SIMULACT do this?" features. I also thank Dr. Susan Conry for her time and effort as she struggled through early versions of this thesis while I developed my writing skills. This work was supported in part through the USAF Laboratory Graduate Fellowship Program under Contract No. S-789-000-020. This work was also supported in part by the Air Force Systems Command, Rome Air Development Center, Griffiss Air Force Base, New York 13441-5700, and the Air Force Office of Scientific Research, Bolling AFB, DC 20332 under Contract No. F30602-85-C-0008. This contract supports the Northeast Artificial Intelligence Consortium (NAIC).

Contents

1	Introduction	1
1.1	Problem Description	1
1.2	Related Work	3
2	Planning as a Distributed Resource Allocation Problem	5
2.1	Problem Class Description	5
2.2	Requirements of Plan Generation	7
3	Distributed Plan Generation	14
4	Implementation	19
4.1	Data Structures	19
4.2	Algorithm Overview	20
4.3	Support Name Operations	22
4.3.1	Support Name Passing	22
4.3.2	Marking Operations	23
5	An Example	26
6	Experimentation	32
6.1	Description of Experiments	32
6.2	Experimental Results	36
6.3	Performance Analysis	46
7	Comparison with Routing Algorithms	48
8	Future Directions	52

List of Figures

2.1	Global Perspective of a Complication	9
2.2	Limited View of Multiple Requests	9
2.3	Multiple Plans That Locally Appear to be One	10
2.4	Initial Blocks World State	11
2.5	Possible Solutions and Global Plans	12
3.1	Multiple Participation of a Single Agent	16
4.1	Frame Structure of Plan Generation Data Objects	20
5.1	Example Network	27
6.1	Line Topology	34
6.2	Ring Topology	35
6.3	Tightly Coupled Topology	35
6.4	Experimental Results: Line Topology	37
6.5	Experimental Results: Line Topology	38
6.6	Experimental Results: Line Topology	39
6.7	Experimental Results: Ring Topology	40
6.8	Experimental Results: Ring Topology	41
6.9	Experimental Results: Ring Topology	42
6.10	Experimental Results: Tightly Coupled Topology	43
6.11	Experimental Results: Tightly Coupled Topology	44
6.12	Experimental Results: Tightly Coupled Topology	45

List of Tables

2.1	Initial Blocks World Plan Fragments	13
5.1	Local Resource Control	27
5.2	Time Slice View of Example	29
5.3	Results of Plan Generation Example	31

Chapter 1

Introduction

1.1 Problem Description

When working with large systems, it is desirable to distribute system information among several problem solving agents. Planning in these distributed domains [15] is distinguished from conventional planning in that plans are composed of sub-plans or plan fragments, each of which represents a solution to a subproblem that is executed by some agent in a multiple agent system. Most of the systems that address planning for distributed domains have assumed that there is a single active planner. This planner knows the capabilities of each agent present in the system and is charged with the responsibility of generating a multiagent plan.

We are concerned with planning for the efficient allocation of distributed resources in multiagent systems where multiple goals coexist. The domains involved are quite large, making it difficult if not impossible to maintain complete, detailed and accurate information about system resources at each agent. Therefore, planning is a process that must be carried out by a group of semi-autonomous agents, each of which has a limited view of the global system state, has control over only a subset of the resources required to satisfy a goal, and has only partial knowledge about the complete set

of resources needed and who controls them. We have developed a planner which operates in two phases, plan generation and multistage negotiation [2]. The plan generation phase determines multiple global plans for satisfaction of each system goal. Multistage negotiation then attempts to determine a set of alternative plans that satisfies the maximum number of global goals, subject to resource constraints. This thesis introduces the plan generation phase of this planner.

Our planner is a distributed planner as opposed to a centralized planner for a multiagent system. Due to the distribution of both the knowledge about system resources and their control, plan generation is dynamic and diffuse in nature. Consequently, a single agent may be asked multiple times to aid in the construction of a global plan. As a result, each agent must be able to determine how multiple requests for partial satisfaction of a single goal fit into that agent's distinct alternatives to satisfy the goal. Is every request part of the same plan? Which requests are actually part of the same alternative and which are the results of distinct plan decompositions? Agents must be able to determine their role in multiple plan decompositions for a single goal with only a limited view of these plans.

Support names are introduced as a means by which each agent can recognize how it participates in various plan decompositions for the same goal without forming global views of these plans. Support names are part of an incremental tagging procedure which allows each agent to recognize its actions in various plan decompositions for the same goal. Agents use support names to construct a limited, abstract view of global information, but no agent is ever provided with complete detailed global information. This is partly due to the maintenance problem described earlier, but more importantly it is *unnecessary* when using our planner.

Plan generation using support names has been implemented in the domain of communications network management. In this system, plan generation determines plans for the restoral of communication service between two users. Through experimentation, we show that plan generation can be accomplished by passing merely a limited amount of information among system agents. All that is required are descriptions of the goal state and the present state of the plan, and information which allows

agents to recognize their past actions in the construction of the plan. This last piece of information is provided through the use of support names. Experimental results show that this distributed mechanism is much faster than a centralized method which provides a single agent with complete details of the entire system. In addition, it does not require the construction of such a global view by any agent.

1.2 Related Work

Our planner differs from existing planners in that certain objects are designated as resources so that they may be efficiently allocated for satisfaction of multiple system goals. Thus, our work represents an extension of the current use of resources in planning. SIPE [26] is a planner which was explicitly designed to handle the notion of resources. However, SIPE uses objects designated as resources for early detection of subgoal interactions among subgoals for the *same* goal. There is no provision made for efficient allocation of resources to satisfy multiple goals. In addition, SIPE is designed for centralized planning, therefore the planner has complete knowledge about the available system resources. It should also be noted that SIPE does allow for the temporary allocation of a resource in the execution of a plan. This is an extension planned for the model presented in this thesis.

The notion of dividing a large problem, and thus a large search space, into smaller problems resulting in regional search spaces is very similar to the planning strategy of GEMPLAN [16]. GEMPLAN is a general constraint satisfaction system which exploits any inherent structure in a given problem domain. The structure of the user's chosen domain is used to identify entities which can be defined as regions where localized constraints can direct a localized search. This structure can take on a hierarchical form whereby one region has access to the subplans of all its subregions. Thus, local search can be used to satisfy local constraints and in fact it may be possible for several subregions to perform their local searches in parallel. Then, moving back up to the regional search space, a regional search can be performed to satisfy regional constraints. Our use of multiple agents with detailed local information is similar to

identifying regions by local constraints. However, our planner does not rely upon a higher level or global search space which can use the results of the local searches to satisfy global constraints.

Systems which perform distributed task decomposition in multiple agents systems do exist. The Contract Net protocol [23] and the distributed NOAH system [4] are perhaps the most well known. The Contract Net protocol performs well in domains where the task can be divided into nearly independent subtasks. Such a decomposition does not require that global information be passed among the agents since interactions among the subtasks are assumed to be nonexistent or unimportant. Thus, no provision is made that allows an agent to reason about multiple participations in the construction of a single plan. Furthermore, for domains such as those described in this thesis, there is no means by which an agent can reason about its participation in *multiple* plan decompositions. The distributed NOAH system does provide mechanisms for an agent to reason about multiple participation in the construction of a single plan. However these mechanisms require complete and accurate information concerning the global plan to be resident at each agent in the system.

Other notable work in Distributed Artificial Intelligence include the research efforts of Durfee and Lesser [6], Rosenschein and Genesereth [22], Georgeff [12], and Cammarata, McArthur and Steeb [1]. The work of these researchers is related to the multistage negotiation phase of our planner.

The following chapter describes the characteristics of distributed planning in more detail and defines the requirements of the plan generation phase. Chapter 3 presents techniques by which the requirements of plan generation are met. Chapter 4 describes the data structures and operations used in our implementation of plan generation. This is followed in Chapter 5 by an example taken from the domain of communications network management. In Chapter 6, experimental results comparing distributed plan generation to other plan generation strategies are presented. In Chapter 7, distributed plan generation as used in the domain of communications network management is compared to conventional routing algorithms. Then in Chapter 8 we describe extensions to distributed planning that should be addressed as research continues.

Chapter 2

Planning as a Distributed Resource Allocation Problem

2.1 Problem Class Description

In many multiagent domains, planning can be viewed as a form of distributed resource allocation problem in which actions require resources in order to satisfy system goals. In such domains, goals require allocation of distributed system resources, but criteria for goal satisfaction are not specified by enumerating the resources required. In fact, the resources required are not known at the time of the instantiation of a goal but are determined as a plan for satisfaction of that goal is constructed. In addition, it is usually the case that there are several combinations of system resources which could be used to satisfy a single goal depending upon the local actions taken by system agents.

The resources which are involved in this class of problems are assumed to be indivisible (not consisting of component resources). Their supply is limited and they cannot be time shared for concurrent satisfaction of multiple goals.

Allocation of a resource in this context has several ramifications. Once a resource is allocated for partial satisfaction of a goal, it is in use as long as this goal is being satisfied. Furthermore, a goal is satisfied only if each and every one of the required resources is currently allocated for this goal. As a result, if even one of these resources is allocated for some other purpose, the original goal is no longer satisfied. Thus, execution of a plan to satisfy a goal implies the concurrent allocation of distributed resources. Moreover, allocation of a resource does not imply consumption of that resource. In fact, it is more than likely that the same resource will be allocated for different purposes at different times as the needs of the system change.

Problems of the type addressed in this thesis are also characterized by their large size. That is, these problems involve vast amounts of detailed information. In addition, this information is constantly being modified. Maintaining a complete, accurate, and detailed view of such a large, dynamic system at each agent is obviously difficult if not impossible. For these reasons it is desirable to limit each agent's view of the entire system. Therefore, control over resources and knowledge about these resources are distributed among problem solving agents. Some of the resources are under the direct control of a single agent, while control over others is *shared* by two agents. Allocation of a shared resource requires coordination between the agents that share its control. In addition, agents have a limited view of the resources that are not under their direct control. Thus, no single agent has complete knowledge about what resources exist in the system or who controls them. As planning progresses, agents do construct abstract views of global information but they never form detailed pictures of global state. This is partly due to the maintenance problem, but more importantly it is *unnecessary* when using the planner described in this thesis.

To illustrate some of these concepts, consider the following blocks world example. Although the amount of information in the blocks world domain is small and therefore does not utilize the power of our planner to the fullest, it is hoped that the following short example will aid the reader. Assume there is a work surface that is shared by two robots, each of which has a private collection of blocks. Furthermore, let us assume that blocks come in two colors, red and blue, that they come in two shapes, rectangular and triangular, and let's assume that blocks come in various sizes. A goal

in this context is to construct a tower where a tower is defined to be a stack of four blocks which have some common property. In addition, the blocks must be placed one upon another in decreasing size. That is, no block can be placed upon another block that is smaller than itself.

In this context, the blocks can be modeled as resources and since each robot has a supply of blocks which it alone controls, neither robot knows the number, size, color or shape of the blocks that the other controls. To avoid a collision of the two robots, the time that a robot can be in the work space is modeled as a shared resource. A plan fragment consists of a sequence of one or more placement operations performed by a single agent at specific times using blocks from its private supply. A global plan consists of a sequence of four placement operations that construct a complete tower. Depending upon the distribution of the blocks, a global plan will consist of placement operations performed by the two robotic arms in various combinations.

2.2 Requirements of Plan Generation

As stated previously, the overall objective of the planner presented is to efficiently allocate system resources so that as many global goals as possible are concurrently satisfied in a multiagent domain.

Distributed plan generation is difficult because each agent must have the ability to recognize its role in global plan decompositions with only a partial view of the global plans in which it participates. As in multiagent systems using a centralized planner, generating an acceptable plan requires problem decomposition and assignment of subtasks to different agents in the system. The major difference lies in the character of the decomposition. In distributed planning the decomposition is *dynamic*, with each agent determining the extent to which it can contribute to satisfaction of a subgoal. Given that contribution, the agent must then determine which other agents may be able to aid in the completion of the plan. The decomposition is also *diffused* in that no agent has knowledge of the entire system state, the entire goal-subgoal

structure, or a complete view of any of the multiple plan decompositions currently under construction. This is due to the fact that both knowledge and control of system resources is distributed among the agents. Using the goal description, agents must dynamically determine what combinations of their resources will satisfy this goal. However, this must be accomplished without any single agent having complete knowledge of what resources exist or who controls them.

A complication arises as a consequence of the dynamic and diffuse nature of plan decomposition. Specifically, a particular agent may be asked to contribute at different times and in different ways to the satisfaction of many subgoals relative to the satisfaction of a single global goal. In order for an agent to correctly determine which of its alternatives can satisfy a particular subgoal, it must be able to assess which subgoals are part of the same global plan decomposition and which are part of distinct decompositions. Those alternatives that are part of the same global plan must be combined into a single alternative. This is necessary for the success of multistage negotiation. During multistage negotiation, agents must be able to reason about the impact of selecting an alternative. In particular, an agent must be able to determine how choosing one plan fragment to satisfy one local subgoal will effect its ability to select plan fragments to satisfy other local subgoals. Execution of a particular plan fragment necessarily limits the resources available for use in satisfaction of other subgoals. Therefore, selection of any specific alternative has potential side effects on the agent's ability to participate in satisfaction of additional global goals. Reasoning about such subgoal interactions can only occur if each available alternative is part of a distinct global plan.

To clarify this point consider Figure 2.1 which depicts a four agent system in which two global plans have been constructed for satisfaction of a single goal. The plans are presented pictorially as sequences of plan fragments distributed among the planning agents. Each plan fragment can be assumed to be a set of local actions which achieve part of the global goal. In particular, notice Agent B's participation in the plan generation phase. Agent B has received two requests to participate in plan construction for this goal. Using the global view presented by Figure 2.1, it is obvious to discern that Agent B should use pf2 as one of its distinct alternatives and pf2 and

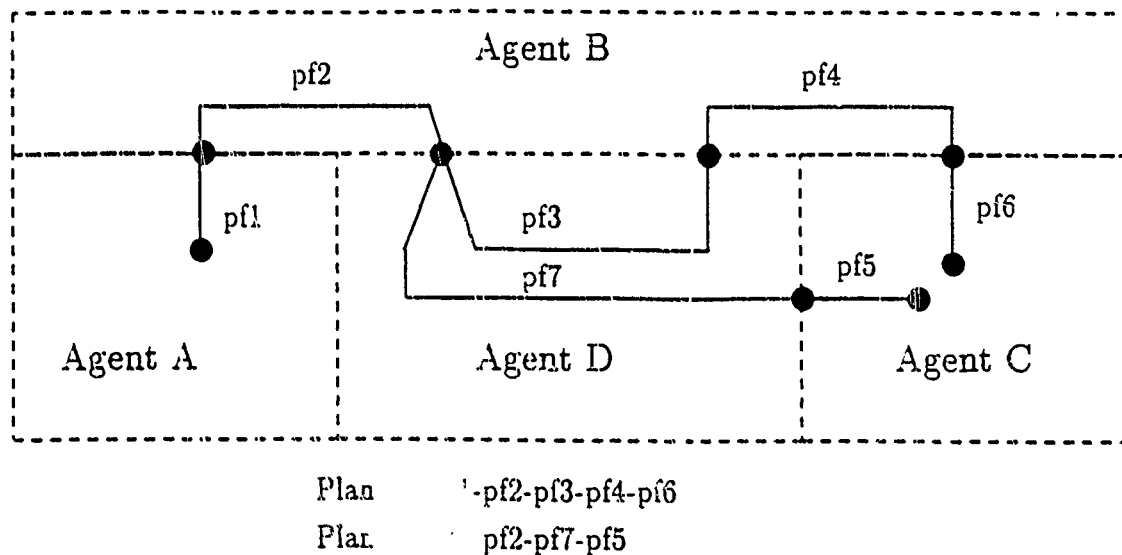


Figure 2.1: Global Perspective of a Complication

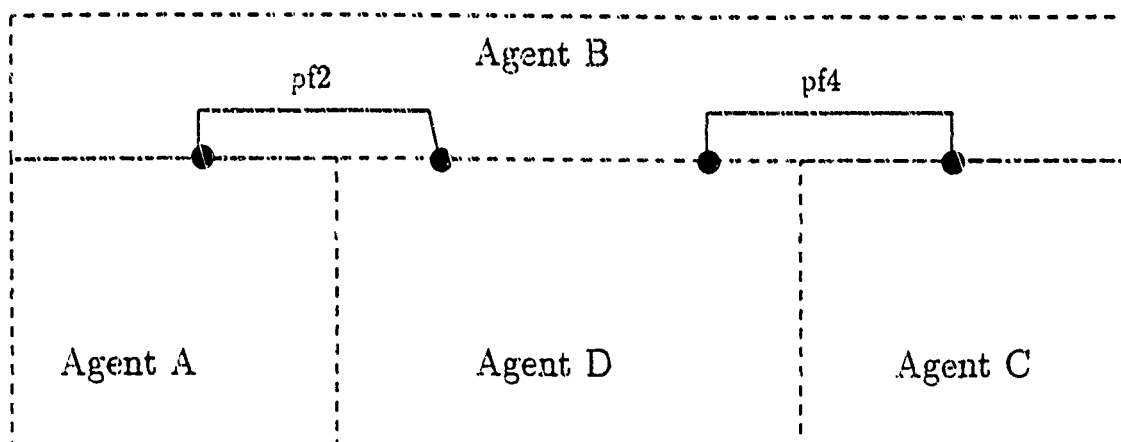
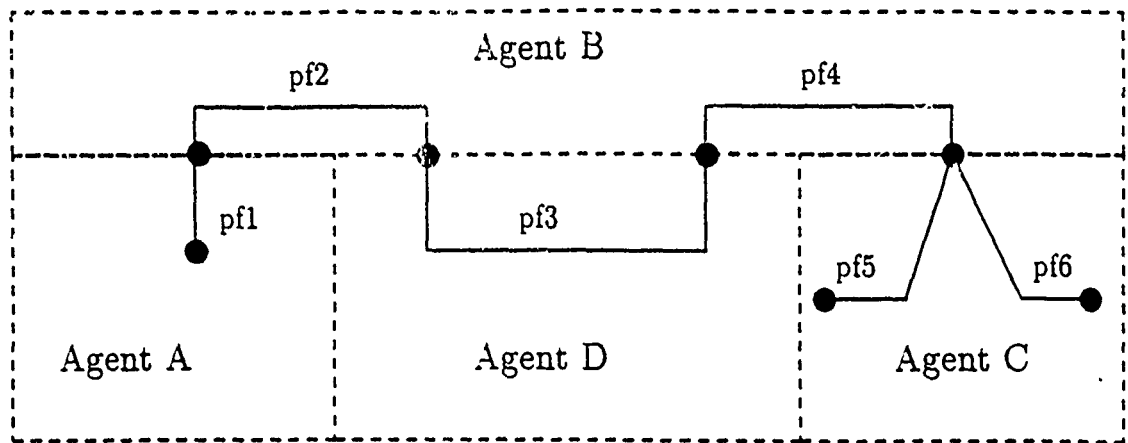


Figure 2.2: Limited View of Multiple Requests

pf4 should be combined into a second distinct alternative for satisfaction of this goal. However, it is important to realize that Agent B *does not* have this global picture. What Agent B "sees" is shown in Figure 2.2. Yet, Agent B must be able to determine how these two requests fit into its distinct alternatives for this goal. Therefore, plan generation must provide some additional information so that agents may formulate distinct alternatives with only a limited view of the multiple plan decompositions created.



Plan 1 : pf1-pf2-pf3-pf4-pf5

Plan 2 : pf1-pf2-pf3-pf4-pf6

Figure 2.3: Multiple Plans That Locally Appear to be One

It should be noted that when an alternative available to an agent appears to be part of a distinct global plan, this is a local perspective. In fact, this alternative may be part of several global plans for the same goal. However, if the agent's participation in each global plan is the same, they locally appear to be a single plan. To clarify this point, consider Figure 2.3 which shows two global plans for a single goal. As before, the plans are presented pictorially as sequences of plan fragments distributed among four planning agents. Once again, notice Agent B's participation in each of the global plans. At the end of plan generation, Agent B should combine plan fragments pf2 and pf4 into a single plan fragment because they represent a single alternative available to Agent B to partially satisfy this goal. From Agent B's limited view, this new plan fragment appears to be part of a single global plan when in reality it is part of two global plans. Whether this new plan fragment is part of a single global plan or multiple global plans is unimportant for the planning performance of Agent B. What is important, is the requirement that Agent B recognize that pf2 and pf4 should be combined into a single plan fragment, because they represent a single alternative for Agent B's participation in partial satisfaction of this goal.

To further illustrate the requirements of plan generation, consider once again the blocks world domain presented earlier. As an example, note the initial state shown

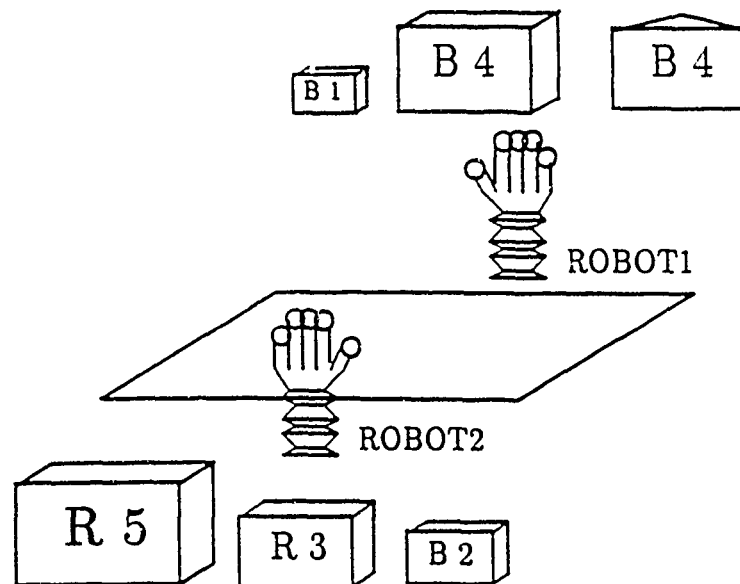
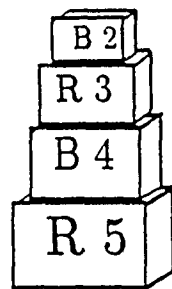


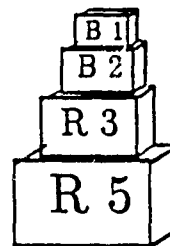
Figure 2.4: Initial Blocks World State

in Figure 2.4. Each block is labeled with an R or B to denote its color and with a number that denotes its size. For the purpose of illustration, let us assume that ROBOT2 has been notified of a goal to construct a tower of rectangular blocks. The possible towers that can be constructed are shown in Figure 2.5 along with a global view of the plan associated with each tower. Table 2.1 shows the resources involved in each of the initial plan fragments created.

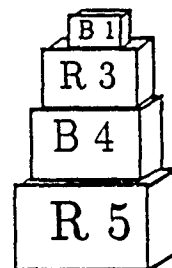
Observe the participation of ROBOT1 in the plan generation process. It has received two requests to aid in the construction of a plan to build a tower of rectangular blocks. These requests resulted in the formation of plan fragments pf3 and pf4. Using the global view of the plans generated as shown in Figure 2.5, it is easy to discern that ROBOT1 has three distinct alternatives if it is asked to participate in a plan to satisfy this goal. One alternative involves the use of plan fragment pf3 alone, one uses plan fragment pf4 alone, and the third alternative involves using both plan fragment pf3 and pf4. However, ROBOT1 does not have this global view. It only knows that it has created two plan fragments as a result of requests to participate in the construction of a plan for this goal. ROBOT1 knows that both of these initial plan fragments are used in conjunction with plan fragments which have been formed



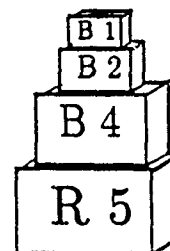
pf1-pf3-pf5



pf2-pf4



pf1-pf3-pf6-pf4



pf1-pf3-pf7-pf4

Figure 2.5: Possible Solutions and Global Plans

Agent	Plan Fragments	Resources			
		Shape	Color	Size	Time Slice
ROBOT1	pf3	Rectangular	Red	4	T2
	pf4	Rectangular	Blue	1	T4
ROBOT2	pf1	Rectangular	Red	5	T1
	pf2	Rectangular	Red	5	T1
		Rectangular	Red	3	T2
		Rectangular	Blue	2	T3
	pf5	Rectangular	Red	3	T3
		Rectangular	Blue	2	T4
	pf6	Rectangular	Red	3	T3
	pf7	Rectangular	Blue	2	T3

Table 2.1: Initial Blocks World Plan Fragments

by ROBOT2, but ROBOT1 does not know the form of ROBOT2's participation in the plans. Therefore, plan generation must provide ROBOT1 with some additional information which will allow ROBOT1 to determine its role in these multiple plan decompositions.

Chapter 3

Distributed Plan Generation

As is clear from the previous discussion, the objective of distributed plan generation is to determine sets of local actions that can be performed in a coordinated fashion by distributed agents to satisfy global goals. Thus, the collection of local actions (in multiple agents) that satisfies a global goal constitutes a global plan that exists as plan fragments distributed among the agents. A plan fragment, then, is a sequence of operator applications to objects under the control of an agent that would transform the global system, possibly through intermediate states, to a new state. When planning is viewed as a resource allocation problem, these operations include allocation of resources local to an agent. An agent can *extend* a plan fragment if the agent can formulate a plan fragment which would transform the system from the proposed new state to a state that is closer to the goal state. As previously indicated, agents have a limited view of resources which are not under their direct control. Thus, each agent has limited knowledge concerning what state transformations other agents can make. Therefore it is impossible, in most cases, for a single agent to devise a global plan.

Plan generation begins when an agent is notified of the instantiation of a global goal. The agent creates a subgoal corresponding to this global goal and determines all sequences of actions it could take to bring the system to a state that locally appears closer to the goal state. Each alternative local sequence becomes a *plan fragment*.

If any of these plan fragments would bring the system state to a new state that is not the goal state, the agent must issue requests for extension of the partial plan to agents that may be able to transform the system from the new state to the goal state or a state that may be nearer to the goal state. The search strategy is a modified version of the means end analysis strategy that has been used in several other planners [7, 8]. The approach in this context is somewhat different in that there is no global information available for an agent to determine whether, in fact, it can bring the system to a state that is closer to the goal state. Using local knowledge, the best each agent can do is determine state transformations that *locally* appear closer to the goal state.

It is clear that every request to extend a plan must carry certain information which will permit an agent to achieve a state that locally appears closer to the goal state. Specifically, a request must contain a description of a global goal, a description of the appropriate intermediate state, and a set of tag lists which are known as support names. Support names embody the information which enables each agent to recognize its own role in multiple plan decompositions without requiring complete knowledge of the global plan.

During plan generation a given agent may be asked to add an additional set of actions to the same global plan several times. Thus it is necessary that an agent be able to detect when it is being asked to build another piece of a global plan it has already partially constructed. If the agent has already built one or more parts of a plan, it must know *which* of its plan fragments were previously used in that plan. This information is needed for two reasons.

First, the agent must determine if it can extend the partial plan in a coherent manner based upon its previous participation in the construction of the plan. Specifically, the agent should not inadvertently build a plan which would bring the system to the same state twice. Permitting the system to cycle through the same state multiple times has two drawbacks: unnecessary work is performed and non-termination is a possibility. In addition, the agent must not allocate more "copies" of any given resource than it has available to a single global plan. Clearly such a plan would involve

demands upon resources which could not be met.

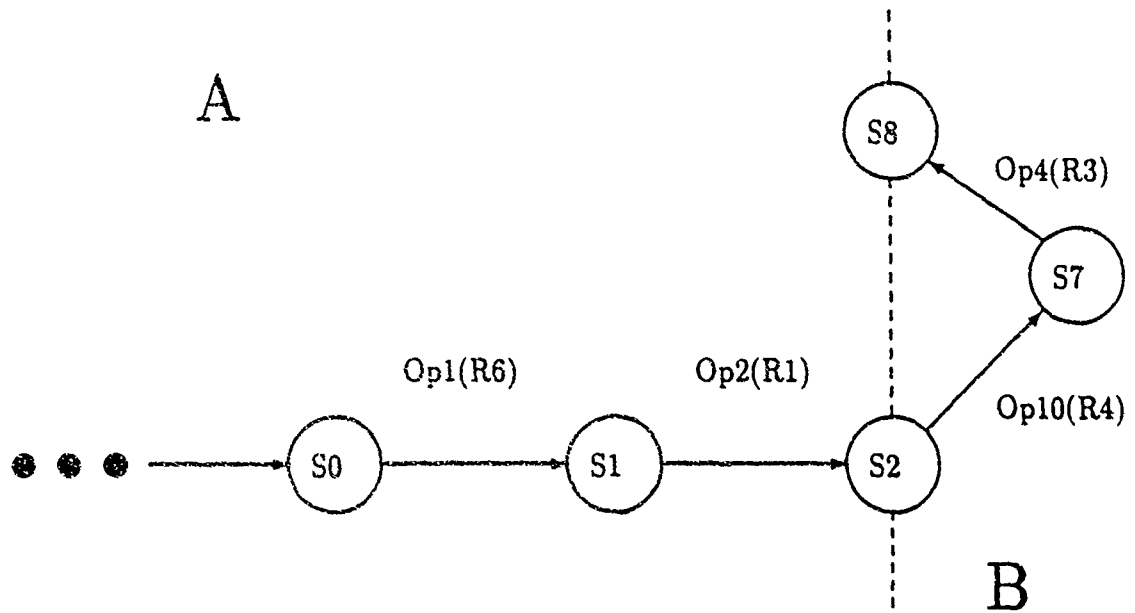


Figure 3.1: Multiple Participation of a Single Agent

To illustrate these concepts, consider Figure 3.1 which depicts plan generation as a series of operator applications that transform a possible plan from state to state. The resources involved in the application of each operator are displayed in parentheses. For the purposes of this example, assume that there is only one copy of each resource mentioned. Agent A has determined that it has one set of actions that would transform the system from state S0 to a new state, S2, that locally appears to be closer to the goal state. This transition involves one intermediate state, state S1. However, in order to reach this new state, Agent A needs to use resource R1 which it shares with Agent B. Therefore, Agent A must coordinate the use of this resource with Agent B. Agent B determines that if R1 is used to reach state S2, it can extend the plan and bring the system to state S8 which locally appears closer to the goal state. Reaching this new state involves coordinating the use of resource R3 with Agent A. The critical issue illustrated here is that if Agent A attempts to fulfill Agent B's request to extend the plan starting from state S8, it must *not* do so by bringing the system through states S0, S1 or S2 because the decomposition of this plan has already been through those states. In addition, Agent A cannot propose an alternative that would use resources R6 or R1, since this plan is already utilizing

those resources, and thus they can not be allocated again. Therefore, Agent A must be able to recognize that it has already participated in this plan decomposition and identify the local plan fragments that are also used in this plan decomposition so that planning for the new request can take place in the proper context.

Furthermore, as discussed in Chapter 2.2, it is the responsibility of plan generation in a single agent to determine when groups of actions that have been formed as part of the same global plan decomposition eventually become components of feasible plans. When this occurs, the agent must gather the actions resulting from the various requests into a single plan fragment. This is required for proper identification of potential subgoal interactions (such as contention for the same resource), where the interactions of concern are those between subgoals for different global goals. As stated before, reasoning about such subgoal interactions can only occur if each plan fragment available to an agent represents a distinct alternative for partial satisfaction of a particular goal.

Our mechanism for providing an agent with the means to recognize distinct roles in multiple plan decompositions involves attaching a list of *support names* to each plan fragment. Support names represent abstractions of the global plans associated with a plan fragment. They are incrementally constructed, with each agent appending a "tag" to identify its own plan fragments. These tags allow an agent to determine how a particular plan fragment is used in a global plan. They *do not* embody information which allows an agent to reason about the specific actions of other agents in a particular global plan. Support names do indicate which agents have participated in the construction of a plan but do not reveal the form of that participation. Since these abstracted plans are constructed incrementally as planning progresses, the support names do not even convey a skeletal structure of the complete plan. Instead, when an agent is requested to extend a plan, it can use each support name that is passed with the request as an abstract history of the construction of a single global plan thus far. This history contains information which allows each agent to recognize if and how it previously participated in the construction of the plan and what other agents aided in the construction of the plan.

Support names follow a plan as it is developed (in a semi-autonomous manner) by the agents. Once a plan has been completed, the requisite plan fragments can be marked by tracing continuation requests using the support name. Thus, an agent can determine which requests are part of the same global plan and which belong to distinct global plans. If it is determined that a plan cannot be completed, the appropriate support names are deleted.

Chapter 4

Implementation

4.1 Data Structures

The basic data objects which are used during plan generation include:

- Subgoals
 - In-subgoal
 - Out-subgoal
- Plan Fragments
- Resources
- Support Names

With the exception of support names, these objects have been implemented as frames in our system. The information contained in each frame, as well as the relationships among these structures, is shown in Figure 4.1. In this diagram, the ovals

indicate the frame being described and the connected lines terminated by a small circle indicate the slots associated with that particular frame. Structure hierarchy which determines slot inheritance, is indicated by arrows. Thus, in this diagram, In-subgoal and Out-subgoal are both Subgoals and they inherit the slots of the Subgoal frame.

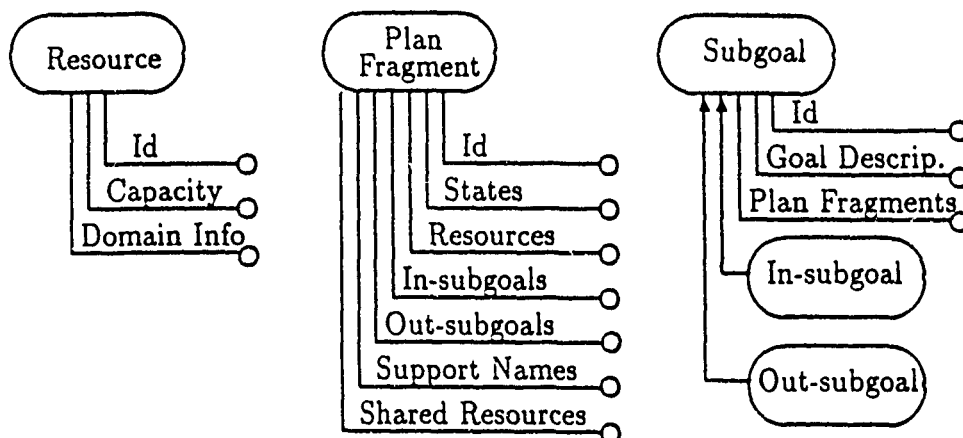


Figure 4.1: Frame Structure of Plan Generation Data Objects

A support name has the form,

$((name) status)$

where *name* is a list of "tags" and *status* is either "ACCEPTABLE" or "UNACCEPTABLE".

4.2 Algorithm Overview

The generation of plans for a goal is initiated when an agent is notified of the instantiation of that goal. The agent instantiates an In-subgoal and performs a local search to form initial plan fragments. For each plan fragment instantiated, the agent checks to see if the goal is satisfied and if it is not, an Out-subgoal is instantiated and a

request to aid in the construction of the plan is sent to the appropriate agent. When an agent receives a request to extend a plan, it creates an In-subgoal and the process is repeated.

Thus, the system can be viewed as a collection of isolated agents that become interdependent through plan generation by a network of In-subgoal/plan fragment/Out-subgoal structures. It is important to make the following observation. When generating multiple plans for the same goal, it is very likely that various subgroups of the plans generated will have steps in common. In particular, an agent may be asked to participate in the same way relative to different plans for the same goal. Each of these requests should result in the formation of the same plan fragments and associated Out-subgoals. Therefore, instead of instantiating new plan fragments and subgoals which duplicate the existing information, the agent should use the existing plan fragments and subgoals.

As stated earlier (see Chapter 3), a support name follows each plan as the responsibility for the plan construction is passed from agent to agent. Using the view of plan generation presented in the previous paragraph, support names are associated with requests to extend plans which are at the forefront of the generation process. Thus, support names are initially coupled with requests that result in the construction of previously non-existent In-subgoal/plan fragment/Out-subgoal arcs. However, as plan generation proceeds, agents will begin to repeat requests for extensions of plans for a goal. One can now think of support names as "riding" the existing In-subgoal/plan fragment/Out-subgoal "arcs". When an agent determines that it is asking another agent to add to a plan in the same way that it asked that agent previously, the agent can merely pass along the support name. The other information necessary for plan generation is already present in the previous request. The only new information is the new support name. This new support name can now be passed along the existing In-subgoal/plan fragment/Outsubgoal arcs until the plan reaches completion, the plan is deemed unacceptable, or the support name "catches up" to the forefront of a plan that is being generated. In the first two cases, an appropriate marking procedure which traces the trail of the plan construction process is initiated. In the last case, the support name is added to those support names associated with

the current request.

4.3 Support Name Operations

As has been mentioned, support name can be viewed as an abstract chronicle of the construction of a plan. Operations are required during the building process which allow an agent to utilize the support name to determine its past actions. This allows the agent to plan in the proper context. Upon completion of the construction process, appropriate marking procedures are required for determination of distinct alternatives. These procedures also utilize the historical information contained in support names. These operations are described in the following paragraphs.

4.3.1 Support Name Passing

Support names are passed among agents either as part of a new request to add to the construction of a plan or as additional information to requests made previously. In either case, when an agent is passed a support name, the following process takes place.

First, the agent determines what plan fragments, if any, can be used to partially satisfy the associated In-subgoal. If this is a new request, a local search is performed and the plan fragments are created. Otherwise, the results of the previous request are used. If no plan fragments for this In-subgoal exist (i.e. the plan cannot be completed), the associated support name is marked unacceptable.

If there are plan fragments for this In-subgoal, the agent must check the support name for tags which it owns. If none exist, then the support name is added to the support names slot of each of the appropriate plan fragments. For each plan fragment that completes an acceptable plan, the support name associated with that

plan fragment is marked acceptable. For each plan fragment which does not complete, a tag which maps to that plan fragment is added to the support name and if an associated Out-subgoal exists, the support name is passed over the existing "arc". If no associated Out-subgoal exists, one is created, and a request for extension of this plan is sent to the appropriate agent.

If the support name contains tags which belong to the agent, the agent must use these tags to determine which of its plan fragments were previously used in the construction of the plan. These plan fragments must then be checked for resource and state conflicts with each of the proposed plan fragments associated with the In-subgoal. If a conflict occurs with each of the proposed plan fragments, the support name is marked unacceptable. Otherwise, the support name is added to the support names slot of each of the non-conflicting proposed plan fragments. For each proposed plan fragment that completes an acceptable plan, the support name associated with that plan fragment is marked "multiple visit" acceptable. The remaining process is identical to that described above. For each plan fragment which does not complete, a tag which maps to that plan fragment is added to the support name and if an associated Out-subgoal exists, the support name is passed over the existing "arc". If no associated Out-subgoal exists one is created, and a request for extension of this plan is sent to the appropriate agent.

4.3.2 Marking Operations

Marking operations are procedures which are associated with a plan fragment frame. The argument to each of these procedures is the support name which is to be marked.

Mark Support Name Acceptable - The support names slot of the plan fragment is searched for the given support name. The status of this support name is then marked acceptable. If the name is not a special symbol denoting that this plan fragment was the first in the construction of this plan, a message is sent to the appropriate agent to continue the marking process. The first tag is stripped off

the current support name and this shortened tag list is passed as the support name to be marked.

Mark Support Name Unacceptable - The support names slot of the plan fragment is searched for the given support name. The status of this support name is then marked unacceptable. Now the agent must check two conditions before propagating this marking process. As with the procedure above, the agent must determine if the given name is a special symbol denoting the first plan fragment in the plan construction. In addition, the agent must check if any of its other plan fragments associated with this goal use this support name. If any of these plan fragments do use this support name and it is not marked unacceptable, then the propagation of marking the support names associated with this plan must end here. What is represented by this situation is a split in the plan. It has been determined that one branch has resulted in an unacceptable plan, but the other branch has either developed into an acceptable plan or the status of that branch of the plan is unknown.

On the other hand, if the marking process should be propagated, then the first tag is stripped from the current support name, this shortened tag list is passed as the support name to be marked and the appropriate agent is notified.

Mark Support Name Multiple Visit Acceptable - The agent searches the given support name for all the tags which it owns. The associated plan fragments are then combined for the instantiation of a new plan fragment frame. A new tag is created which can be mapped to this new plan fragment. A new support name is formed by replacing each of the tags which this agent owns in the given support name with the new tag. This new support name is placed in the support names slot of the new plan fragment and its status is marked acceptable. The support names slot of the given plan fragment is searched for the given support name and it is marked unacceptable. Next, the first tag is stripped off the first tag of the new support name and the appropriate agent is notified to add this support name to the appropriate plan fragments and mark its status acceptable.

Add Acceptable Support Name - The given support name is marked acceptable and is added to the support names slot of the given plan fragment. If the

name is not the special symbol denoting that this was the first plan fragment used in the plan construction, then the appropriate agent is notified to add an acceptable support name. The first tag is stripped off the current name, forming the support name that is passed.

Chapter 5

An Example

To illustrate the use of support names, an example taken from the domain of communications network management is presented. Consider the communications network shown in Figure 5.1. There are five problem solving agents, each controlling part of a network of geographically distributed communication facilities. The network partitions are called subregions, the circles represent communication sites and the lines joining sites represent communication links. In this domain, the problem of restoring disrupted service can be viewed as a planning problem in which one operator, *Allocate*, is utilized to allocate communication resources. In this simple example, the only resources are links and a global plan is a collection of local connections each of which allocate a link to restore communication between two sites. A partial plan or plan fragment involves an allocation of resources that transforms the system from a state in which it has a path ending at one site to one in which it has a new path ending at another site. The availability of a resource depends upon its use by currently existing circuits or circuits whose service has been disrupted. Links which span subregion borders are controlled by the resident subregions of their endpoints. Links such as these are modeled as shared resources. In addition, no global topological information exists. Agents only know about the links they control directly and those they share. Thus, if one agent needs the aid of other agents to construct a plan in this domain, it asks those agents with whom it shares the control of a resource.

Table 5.1 summarizes the knowledge about resources available to each agent and the associated control relationships.

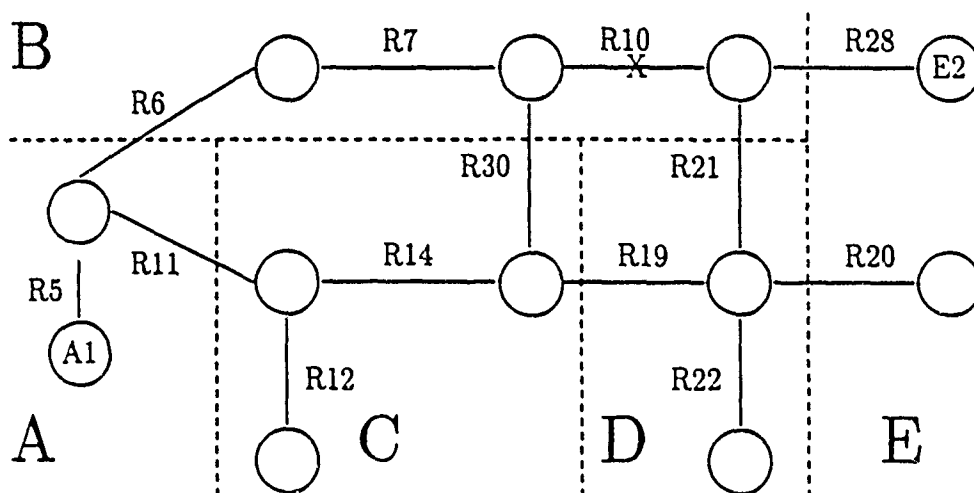


Figure 5.1: Example Network

Agent	Resources
A	R5 R6 R11
B	R6 R7 R10 R21 R28 R30
C	R11 R12 R14 R19 R30
D	R19 R20 R21 R22
E	R20 R28

Table 5.1: Local Resource Control

For the purpose of this example, assume that originally communication between sites E2 and A1 followed a path over links R28-R10-R7-R6-R5, but link R10 has failed and communication between sites E2 and A1 must be restored over a different route. Furthermore, suppose that Agent E is notified that a global goal to restore the path between sites E2 and A1 has been instantiated.

It is perhaps easiest to explain how plan generation proceeds by viewing the activities of agents at global time slices (see Table 5.2). The actions presented in each time slice are described in two parts. The first part identifies a planning agent

and what action is being taken by that agent. The second part is either a description of the action or a result returned by the action. The latter is denoted by a preceding arrow. The following legend describes the forms used in Table 5.2:

local subgoal	<i>description</i>
local search	<i>(plan-fragment, resources-to-allocate, support-name-added)</i>
request agent	<i>extend(goal, shared-resource-to-use, support-name-to-add)</i>
notify agent	<i>remove(goal, resource-used, support-name-to-remove)</i> <i>acceptable(goal, resource-used, acceptable-support-name)</i> <i>add support(goal, resource-used, support-name-to-add)</i>
remove support	<i>remove-support(matching-plan-fragment, support-name-to-remove)</i>
acceptable support	<i>mark-acceptable(matching-plan-fragment, acceptable-support-name)</i>
add support	<i>add-support(plan-fragment, support-name-to-add).</i>

The example begins with Agent E instantiating a subgoal to restore a communications path from site E2 to site A1. Agent E then conducts a local search and determines that it has one alternative that locally satisfies this subgoal, pfE1, which uses resource R28. Since Agent E has initiated the plan generation process, there is no previous support to associate with this plan fragment. Thus, a "*" is used to denote this situation. Control over resource R28 is shared with Agent B, therefore, a request is sent asking Agent B to extend the plan for this goal using this shared resource, R28, with support name (E1). Plan generation continues from this point.

Observe time slice T4. Here Agent E has determined that it has no alternatives which extend Agent D's request. Therefore, Agent E notifies Agent D that the support name that followed this plan decomposition should be removed. In time slice T5, Agent D uses the destination and resource in Agent E's notification to identify plan fragment pfD1 and Agent D removes the appropriate support name from this plan fragment.

In time slice T6, when Agent A completes a global plan using a request from Agent B, it sends back a notification to Agent B that the request has resulted in an

T1	E: subgoal E: local search E: request B	to restore path from E2 to A1 → (pfE1, (R28), *) extend (A1, R28, (E1))
T2	B: local subgoal B: local search B: request D	to A1 using R28 → (pfB1, (R28, R21), (E1)) extend (A1, R21, (B1, E1))
T3	D: local subgoal D: local search D: request E D: request C	to A1 using R21 → (pfD1, (R21, R20), (B1, E1)) → (pfD2, (R21, R19), (B1, E1)) extend (A1, R20, (D1, B1, E1)) extend (A1, R19, (D2, B1, E1))
T4	C: local subgoal C: local search C: request A C: request B E: local subgoal E: local search E: notify D	to A1 using R19 → (pfC1, (R19, R14, R11), (D2, B1, E1)) → (pfC2, (R19, R30), (D2, B1, E1)) extend (A1, R11, (C1, D2, B1, E1)) extend (A1, R30, (C2, D2, B1, E1)) to A1 using R20 → no alternatives remove (A1, R20, (D1, B1, E1))
T5	A: local subgoal A: local search A: notify C B: local subgoal B: local search B: request A D: remove support	to A1 using R11 → (pfA1, (R11, R5), (C1, D2, B1, E1)) acceptable (A1, R11, (C1, D2, B1, E1)) to A1 using R30 → (pfB2, (R30, R7, R6), (C2, D2, B1, E1)) extend (A1, R6, (B2, C2, D2, B1, E1)) remove-support (pfD1, (B1, E1))
T6	A: local subgoal A: local search A: notify B C: acceptable support C: notify D	to A1 using R6 → (pfA2, (R6, R5), (B2, C2, D2, B1, E1)) acceptable (A1, R6, (B2, C2, D2, B1, E1)) mark-acceptable (pfC1, (D2, B1, E1)) acceptable (A1, R19, (D2, B1, E1))
T7	B: new plan fragment B: remove support B: notify C B: notify C D: acceptable support D: notify B	combine (pfB3, (pfB1, pfB2), (C2, D2, B3, E1)) remove-support (pfB2, (C2, D2, B1, E1)) remove (A1, R30, (C1, D2, B1, E1)) add support (A1, R30, (C1, D2, B3, E1)) mark-acceptable (pfD2, (B1, E1)) acceptable (A1, R21, (B1, E1))
T8	B: acceptable support B: notify E C: add support C: remove support C: notify D	mark-acceptable (pfB1, (E1)) acceptable (A1, R28, *) add-support (pfC2, (D2, B3, E1)) remove-support (pfC2, (D2, B1, E1)) add support (A1, R19, (D2, B3, E1))
T9	D: add support D: notify B E: acceptable support	add-support (pfD2, (B3, E1)) add support (A1, R21, (B3, E1)) mark-acceptable (pfE1, *)
T10	B: add support	add-support (pfB3, (E1))

Table 5.2: Time Slice View of Example

acceptable plan. Agent B receives this notification in time slice T7 and determines that it owns two of the tags in the support name associated with the request. Agent B identifies pfB2 and pfB1 with these tags and thus realizes that they are part of a single plan decomposition that has resulted in an acceptable plan. Therefore, Agent B creates a new plan fragment, pfB3, which uses the resources of both pfB2 and pfB1 and Agent B gives this new plan fragment support. Since no acceptable global plan uses pfB2 alone, its support names are removed.

Note that in time slice T8, Agent C removes a support name from pfC2 due to the propagation of support name removal started in Agent B. However, this propagation ends here because there is another plan fragment, pfC1, which uses the same support name (see T4). This represents a place where the search for a global plan split into two parallel search paths. In this example, the second plan fragment that uses the same support name has been marked as part of an acceptable global plan in time slice T6. The propagation of this acceptable support name has reached Agent B in this time slice. Agent B is notified that pfB1 is part of an acceptable plan. Using the support name, Agent B determines that pfB1 is part of an acceptable global plan that does not use other plan fragments in Agent B. As a result, the support names for pfB1 are marked acceptable.

Table 5.3 shows the plan fragments created by each agent, the resources used by these plan fragments, and the support names associated with each plan fragment at the end of plan generation. Note that pfD1 has no support names because this plan fragment is not part of any acceptable global plan.

To summarize the important points of this example, Agent B created two plan fragments, pfB1 and pfB2, as a result of requests to add to partially constructed plans for the same global goal. Through the use of support names, Agent B has determined that pfB1 and pfB2 are used in one set of acceptable global plans (in this case one plan) and pfB1 is also part of a different set of acceptable global plans (also one plan in this example). When pfB1 and pfB2 are used as parts of the same global plan, they represent a single alternative in Agent B for this global plan. This has been reflected by the creation of pfB3. The determination of how these plan fragments,

Agent	Plan Fragments	Resources	Support Names
A	pfA1	R11-R5	(C1 D2 B1 E1)
	pfA2	R6-R5	(B2 C2 D2 B1 E1)
B	pfB1	R28-R21	(E1)
	pfB2	R30-R7-R6	none
	pfB3	R28-R21 R30-R7-R6	(C2 D2 B3 E1)(E1)
C	pfC1	R19-R14-R11	(D2 B1 E1)
	pfC2	R19-R30	(D2 B3 E1)
D	pfD1	R21-R20	none
	pfD2	R21-R19	(B1 E1)(B3 E1)
E	pfE1	R28	*

Table 5.3: Results of Plan Generation Example

created out of separate requests, fit into global plans has been accomplished without any single agent having complete knowledge about any of the acceptable global plans generated.

Chapter 6

Experimentation

6.1 Description of Experiments

Research in distributed planning is currently being conducted in the context of the communications domain described in the previous example. The implementation model¹, however, contains much more of the detail associated with a real world communications network [3]. Local searches for plan fragments are not simple searches for paths of links in and out of a subregion as might be assumed given the example above. On the contrary, local searches involve tracing through complex interconnections of various types of communications equipment at the sites within a subregion.

Existing planners use several different architectures and moreover, the level of abstraction at which planning occurs varies from system to system. Experiments have been conducted so that distributed plan generation as presented in this thesis may be

¹The methods described in this thesis have been implemented on a TI Explorer in Common Lisp. Simulation of the multiagent processing has been accomplished through the use of SIMULACT [18].

compared to plan generation schemes with various architectures using different levels of abstraction. In each of the tested schemes, an agent which has control over part of a network has detailed information about that part of the network and *only* that part of the network. If any other information is used for plan generation, it is either abstract knowledge in the form of plan fragments, or limited, abstract knowledge in the form of support names. The following is a description of the plan generation paradigms used in these experiments. The first is a single agent system and the rest are multiple agent systems.

Single Agent/Detailed Global View (SA/DGV) A single agent is responsible for the entire system rather than distributing system knowledge among multiple agents. In this approach, a local search for plan fragments is equivalent to a global search for global plans that will satisfy system goals.

Multiple Agent/Limited Abstract Global View (MA/LAGV) This is the approach described in this thesis. Plans are constructed by multiple agents which have an incomplete, limited view of the global plans. This incomplete, limited view is determined by the incremental construction of support names and therefore, is different at each agent in the system.

Multiple Agent/Central Abstract Global View (MA/CAGV) Agents use the descriptions of the circuits which are to be restored to determine all the possible ways they might be able to participate in a global plan. The results of these local searches are sent to a single agent who pieces the plan fragments together into acceptable global plans. Once this is completed, each agent is notified of its participation in global plans. The view of this single planning agent is not limited in the sense that it does know about the complete set of plan fragments in the system. However, its view is abstract since this agent knows nothing about the detail of communications equipment and its interconnection at each site.

Multiple Agent/Replicated Abstract Global View (MA/RAGV) As in the MA/CAGV approach, local searches are conducted by each agent using high level circuit descriptions. The results of these searches, however, are sent to

every other agent in the system. Then, with complete knowledge of every plan fragment in the system, each agent forms the global plans and determines its own role in each.

The key parameters monitored in these experiments are the simulated time required to generate plans, the average cpu time required by each processing node to generate plans, and the amount of message traffic sent during the simulation.

In addition, three network configurations were chosen to observe the effect of various topological extremes. In this domain, the network topology actually defines the complexity of the roles of agents in the multiple plan decompositions. Therefore, by varying these topological extremes it is also possible to observe the performance of these strategies when agent participation takes on roles of different complexity. Each network contains twelve sites divided into five subregions with various inter- and intrasubregion connectivity. Figure 6.1 shows the configuration where the subregions are connected in a straight line and Figure 6.2 shows the subregion connections which form a ring. The third topology chosen is shown in Figure 6.3. Here each subregion is connected to every other subregion creating a tightly coupled network.

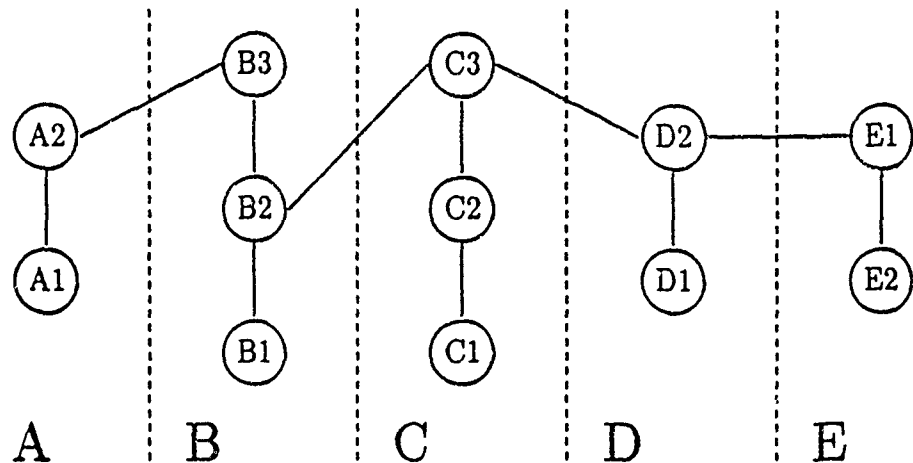


Figure 6.1: Line Topology

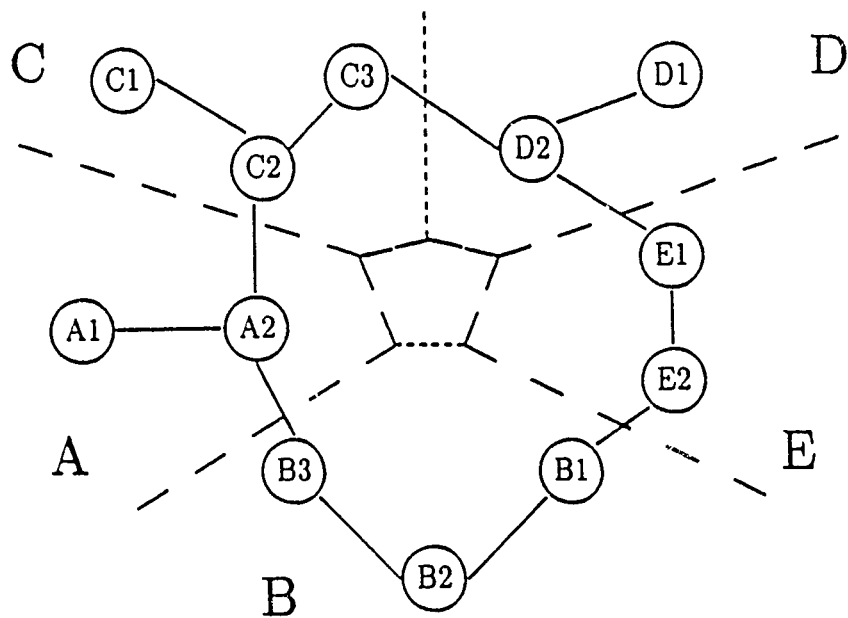


Figure 6.2: Ring Topology

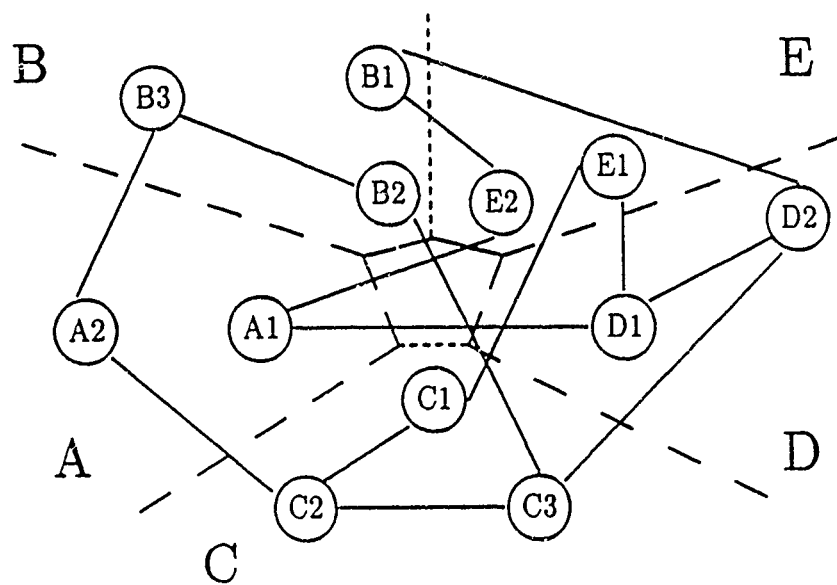


Figure 6.3: Tightly Coupled Topology

6.2 Experimental Results

The results of these experiments are shown in Figures 6.4, 6.5, 6.6, 6.7, 6.8, 6.9, 6.10, 6.11, and 6.12. As expected, the SA/DGV strategy performs the worst in terms of the time taken to devise global plans. This observation holds true over each of the tested topologies. This points to the desirability of distributed multiagent systems over centralized single agent systems when the systems are large.

The MA/CAGV, MA/RAGV, and MA/LAGV strategies all take about the same amount of time to determine global plans for the line topology. As well, the cpu time per agent is approximately the same. However, the amount of message traffic required by the MA/RAGV strategy exceeds that of both the MA/CAGV and MA/LAGV strategies with the MA/CAGV strategy performing better as the number of goals grows.

For the ring topology, the cpu time per agent for the multiagent strategies begins to separate with the MA/CAGV strategy clearly performing better as the number of goals increases. The MA/RAGV and MA/LAGV strategies appear to be following approximately the same line. Regarding the time to construct global plans, the MA/RAGV and MA/CAGV strategies outperform the MA/LAGV when the number of goals is small. However, as the number of goals increases, the lines appear to be converging. The results for the message traffic required shows that the MA/RAGV and MA/LAGV strategies have approximately the same requirements while the MA/CAGV strategy requires less message traffic.

When the topology is tightly coupled, the strategies perform with significant differences. The MA/LAGV strategy clearly requires less time than both the MA/CAGV and MA/RAGV to devise plans as the number of goals increases. However, the cpu time per agent required is clearly less for the MA/CAGV strategy with the MA/LAGV strategy coming in second and the MA/RAGV performing worse. In addition, there is a marked difference in the amount of message traffic required by the different strategies. The MA/LAGV strategy requires the most message traffic, the MA/RAGV less,

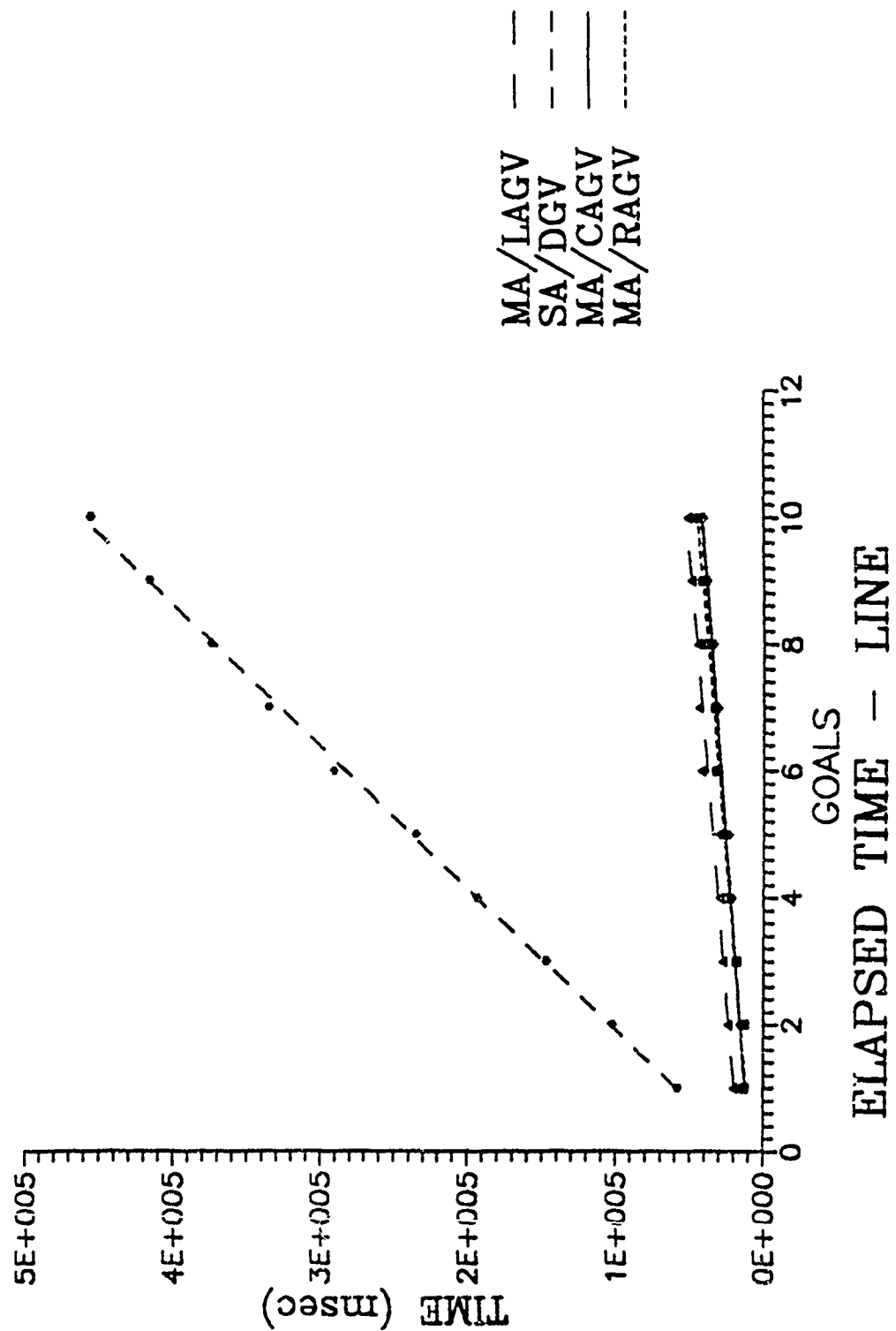


Figure 6.4: Experimental Results: Line Topology

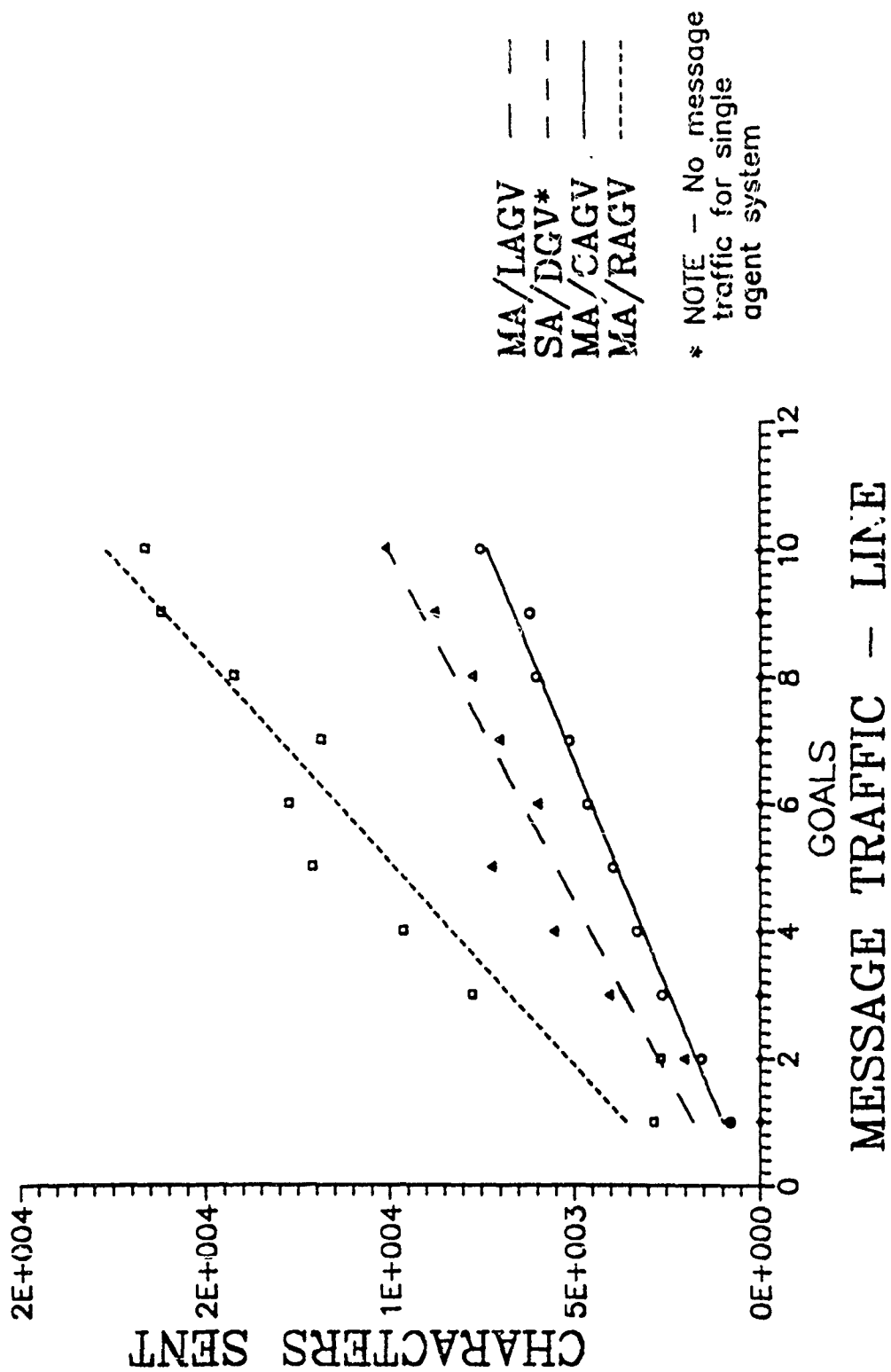


Figure 6.5: Experimental Results: Line Topology

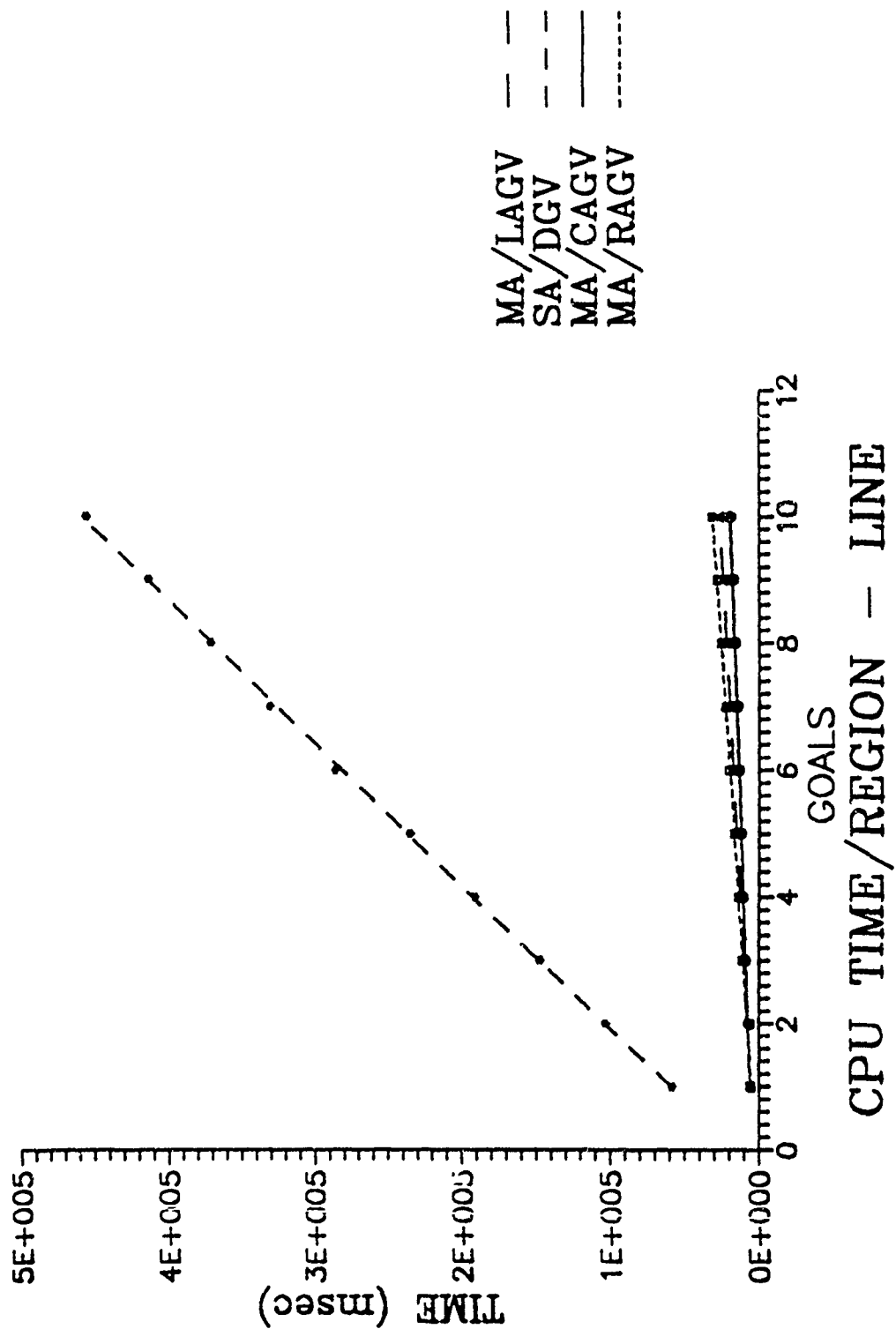


Figure 6.6: Experimental Results: Line Topology

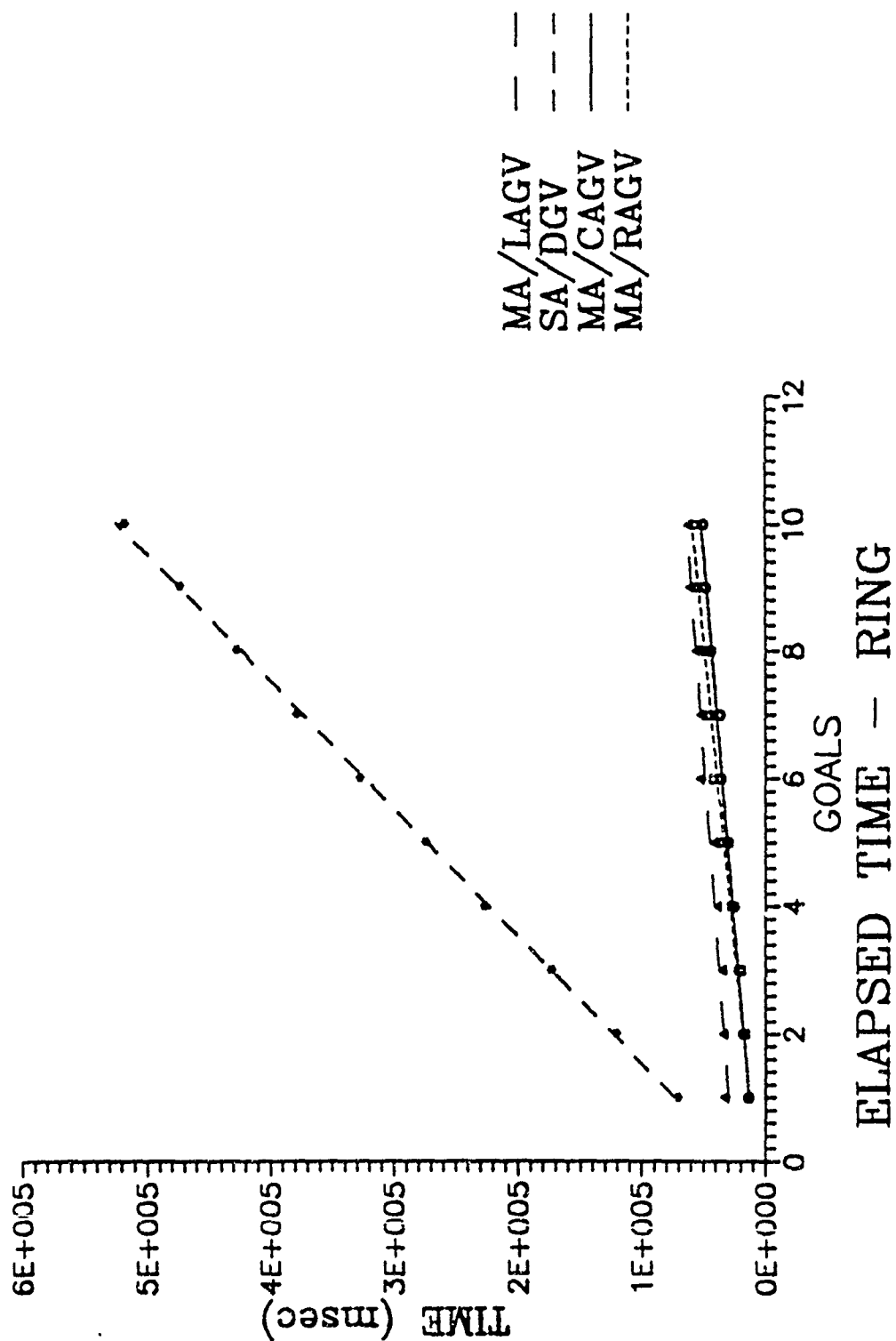


Figure 6.7: Experimental Results: Ring Topology

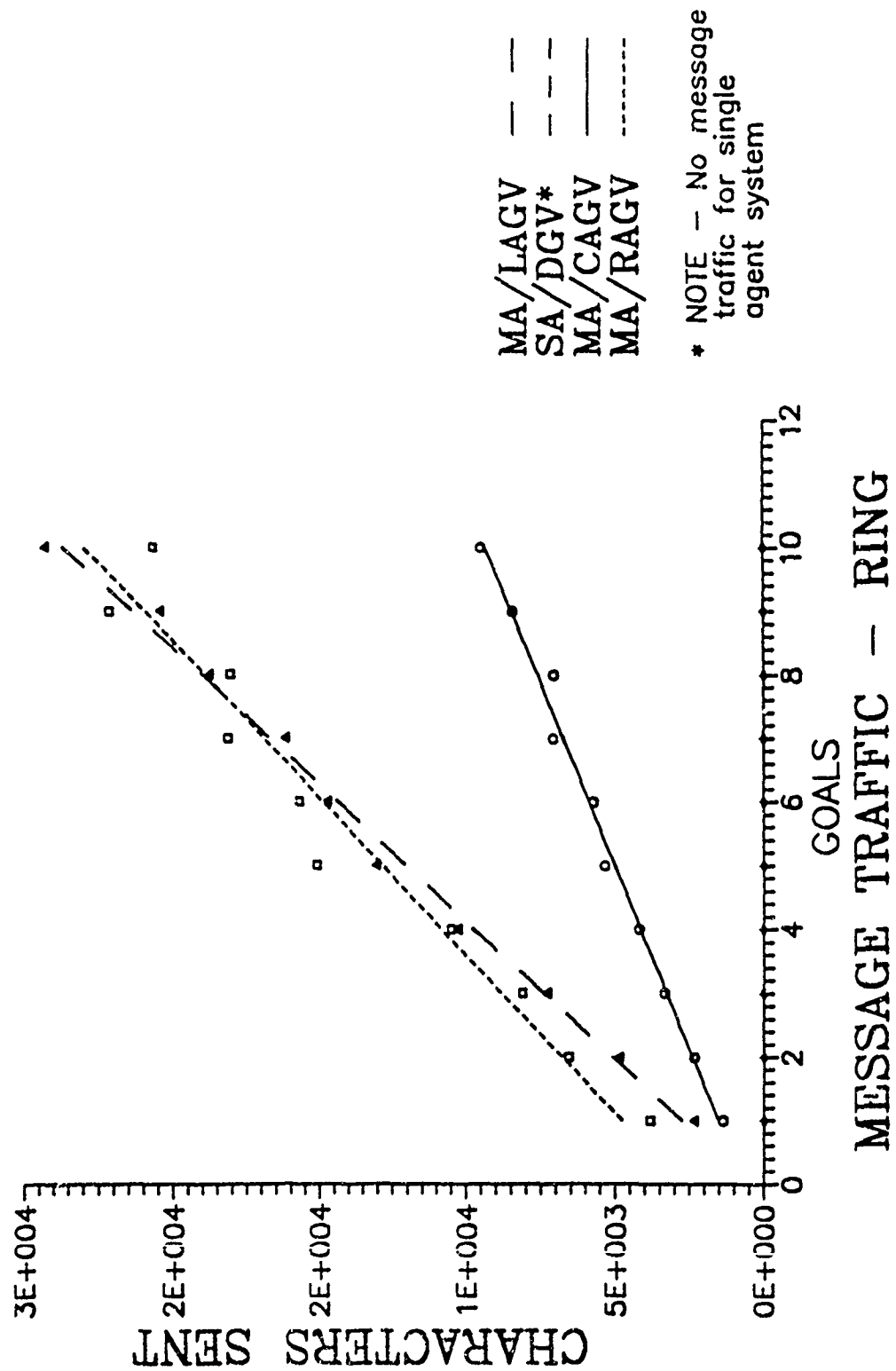


Figure 6.8: Experimental Results: Ring Topology

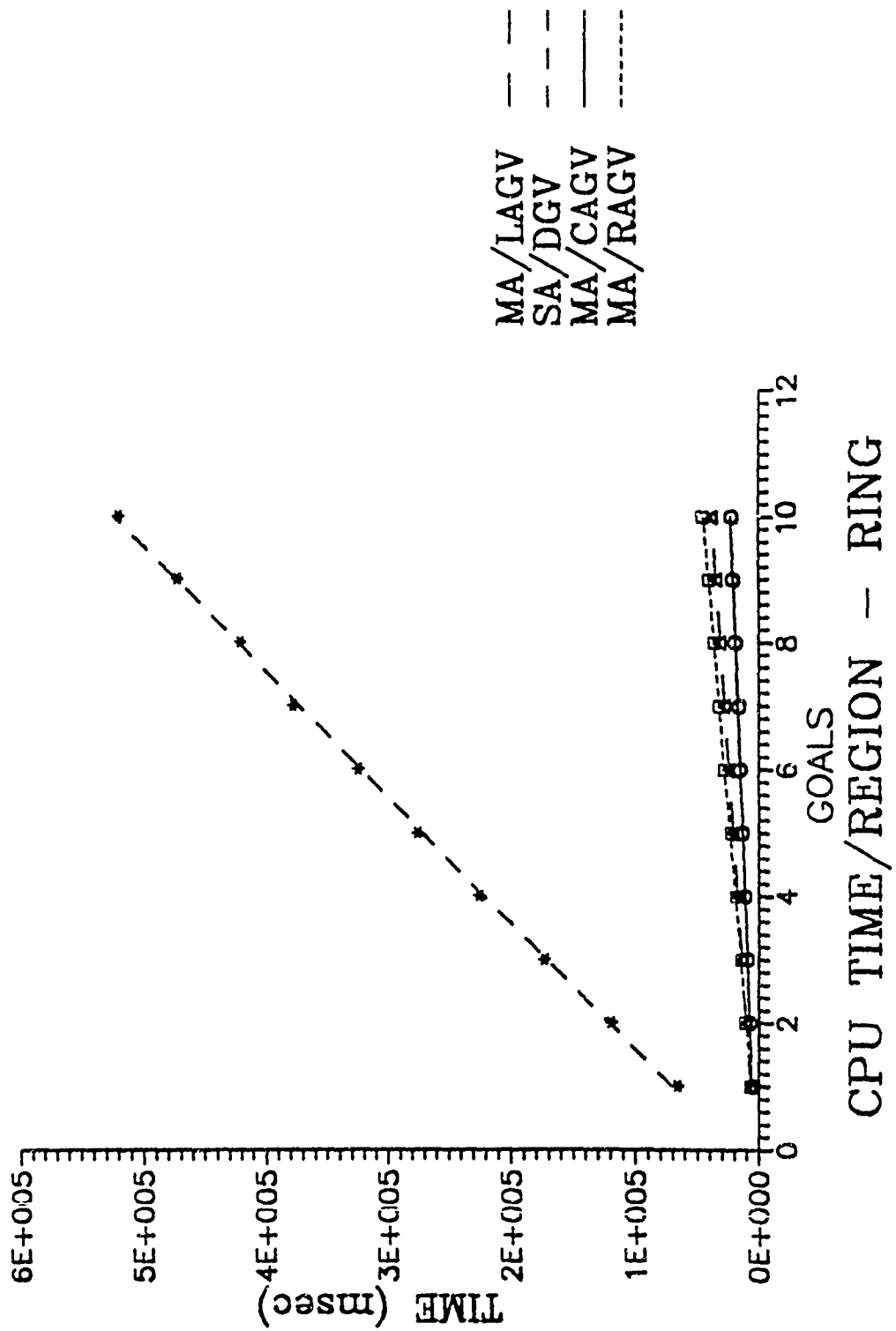


Figure 6.9: Experimental Results: Ring Topology

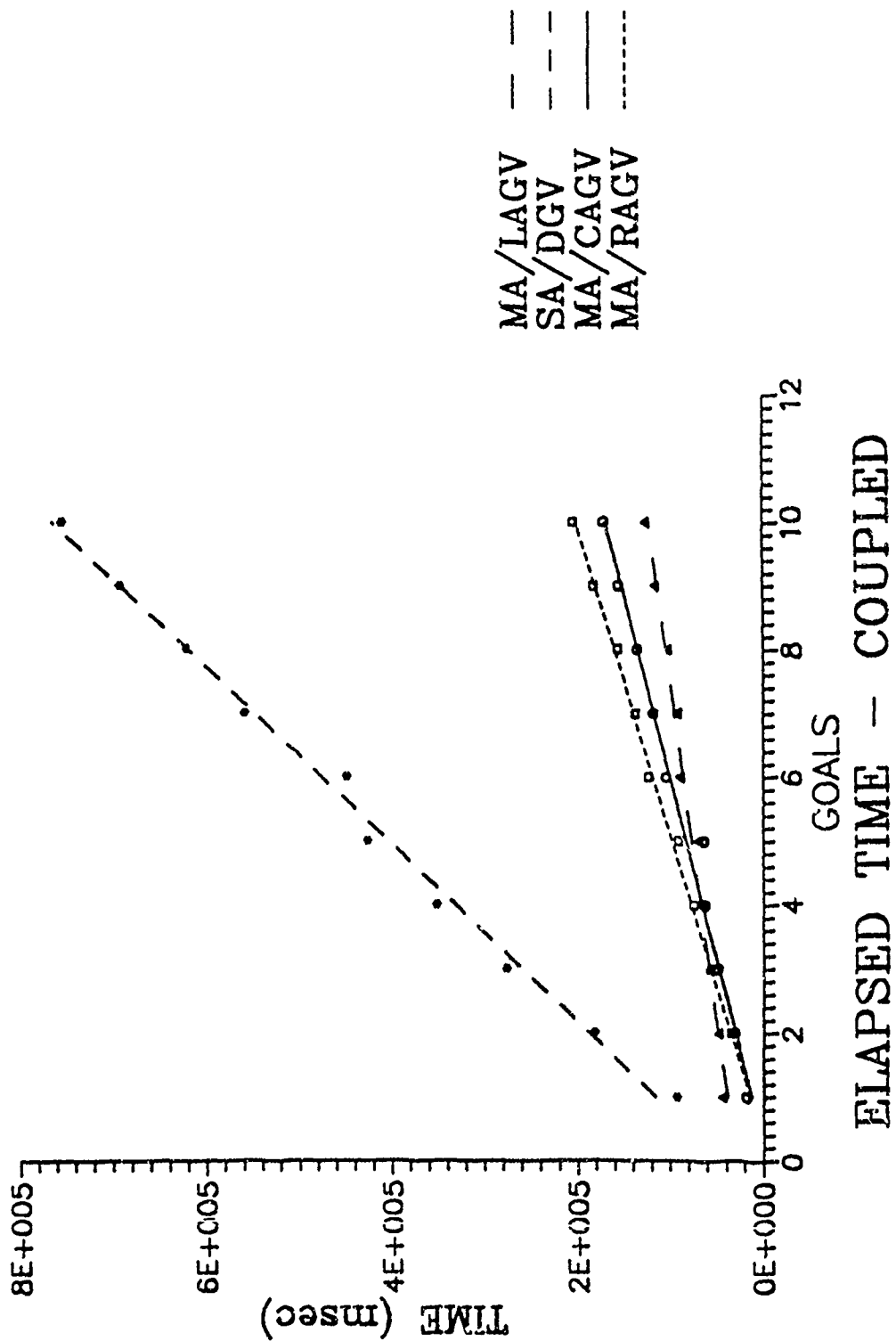


Figure 6.10: Experimental Results: Tightly Coupled Topology

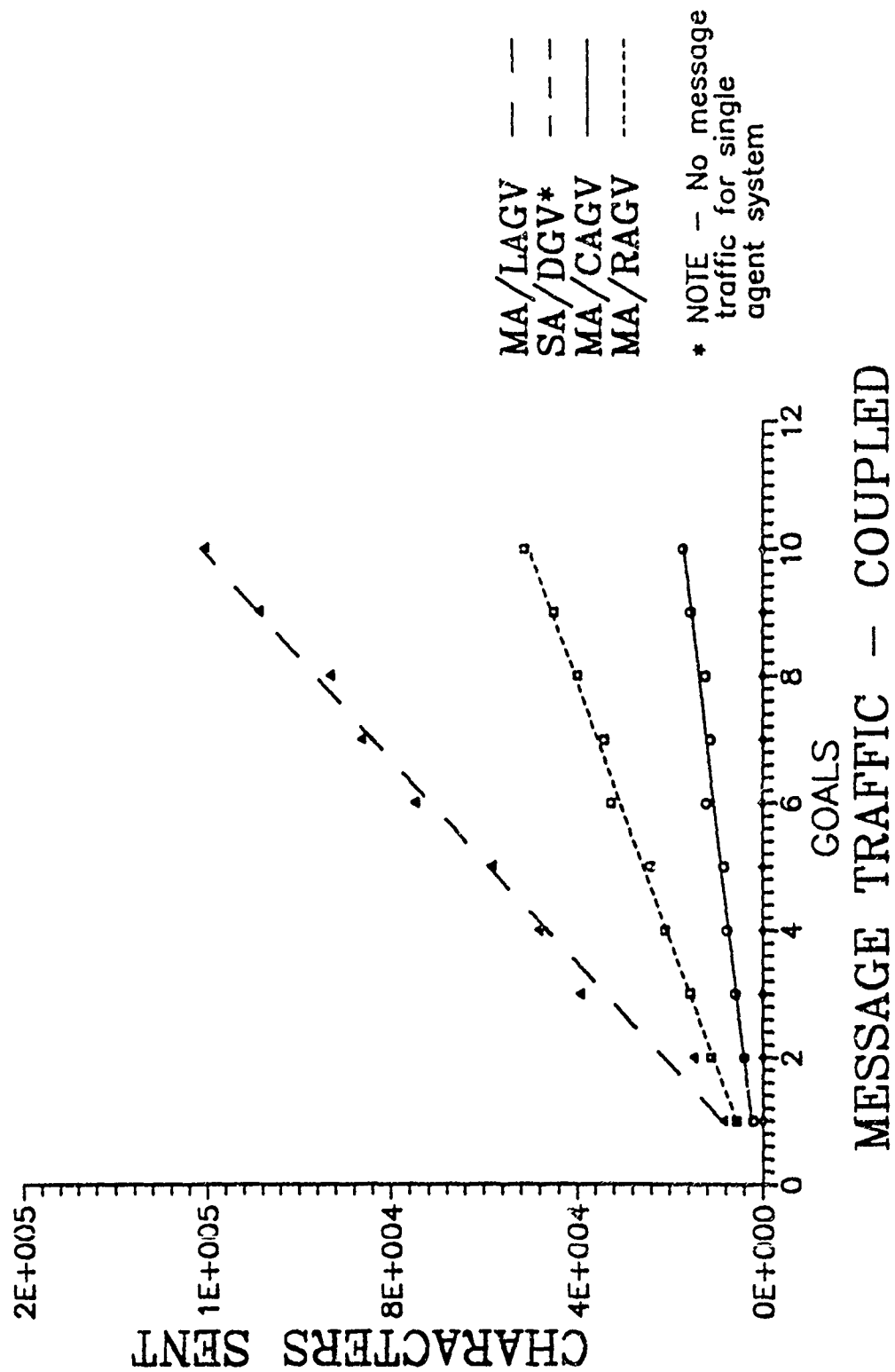


Figure 6.11: Experimental Results: Tightly Coupled Topology

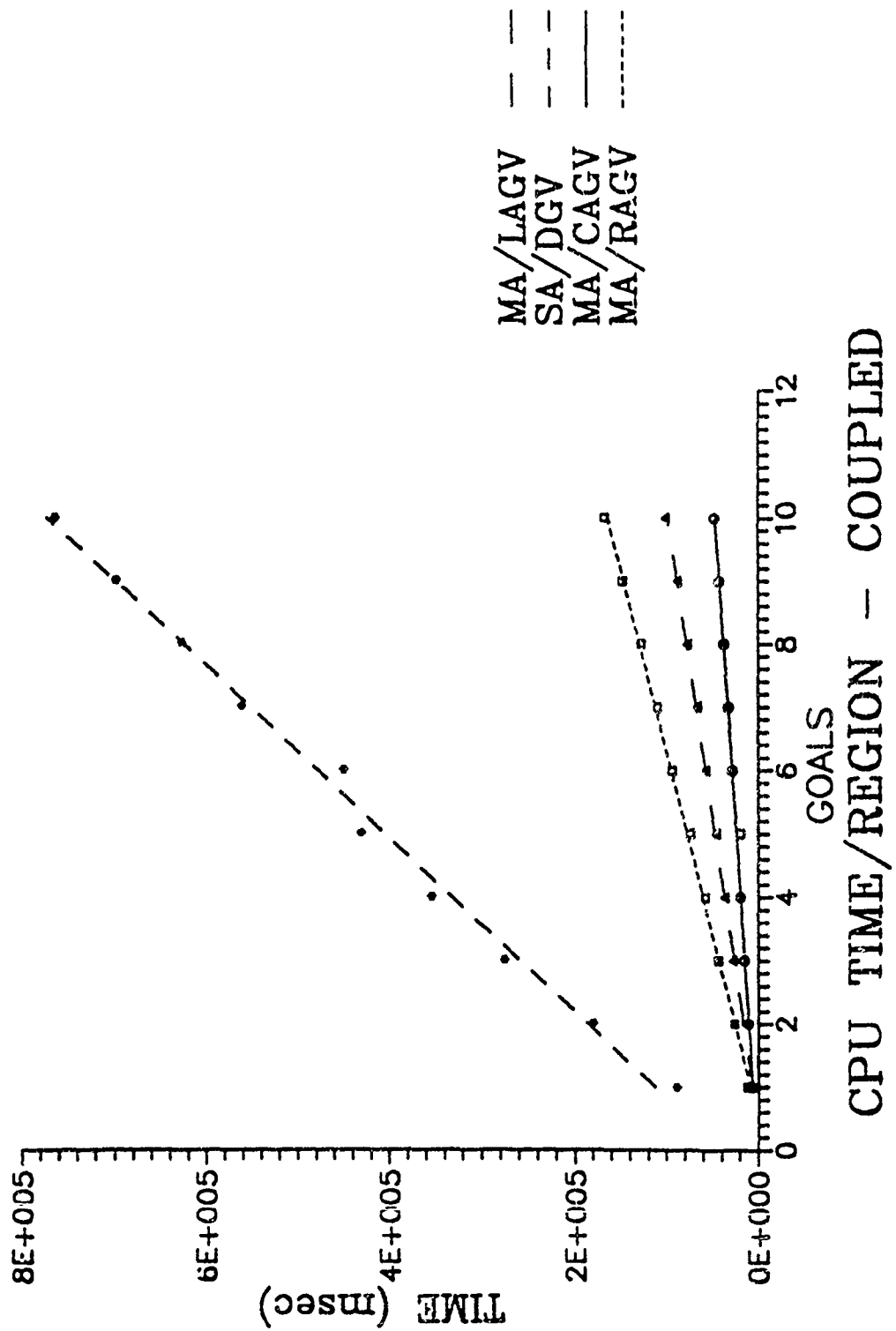


Figure 6.12: Experimental Results: Tightly Coupled Topology

and the MA/CAGV still less.

For the network topologies tested, there is a clear question of trade offs. For the ring and line topologies, the MA/CAGV strategy performs better overall. The price paid however is vulnerability. In domains where survivability is an important concern, such as a military communications network, the MA/CAGV strategy obviously is undesirable because of the dependence upon a single agent. For the tightly coupled topology, the MA/LAGV strategy will take less time to construct plans but the price paid is in the amount of message traffic required.

6.3 Performance Analysis

The performance of distributed plan generation can be analyzed by considering the time required to generate plans and the amount of message traffic sent.

The time required to generate plans is influenced by factors on two levels. At one level, this parameter is dependent upon the amount of time required to pass the plan among each of the agents involved in its construction. Therefore, from a global viewpoint, the time required to generate plans is directly related to the length of the longest chain of agents involved in building a plan. At another level, the amount of time required to generate plans is determined by the processing time of each individual agent. As the relations between requests to extend a plan and multiple plan decompositions become more complex, so does the processing involved to determine distinct alternatives. Thus, from a global perspective, the time required to generate plans is also directly related to the complexity of the roles of agents in multiple plan decompositions.

The message traffic necessary for plan generation is also directly related to the participation of agents in multiple plan decompositions. When an agent is notified that a plan it has helped to build has been deemed acceptable, that agent is responsible for the propagation of this information. If the agent participated only once in the plan

construction, a single message is required to continue the propagation. However, if the agent participated multiple times in the construction, then two messages are sent, one to propagate the new support name and one to remove the old support name. Thus, the message traffic required to generate plans increases as the complexity of the roles of agents in multiple plan decompositions increases. However, it should be noted that the amount of message traffic required does not approach that which would be needed to transmit complete, detailed global information to each agent in the system.

These experiments illustrate that distributed plan generation can be accomplished by passing merely a limited amount of information among system agents. The only information required includes descriptions of the goal state and the present state of the plan, and information which allows agents to determine their previous actions in the construction of the plan. This last piece of information is provided by the implementation of support names. Experimentation shows that building a complete, detailed global view at any agent is unnecessary. Plan generation using support names will perform best in domains where goals can be satisfied through the actions of a small number of agents who participate in the construction of plans only once. The performance of distributed plan generation using support names will degrade as the number of requests for extensions of plans grows and as the number of times agents participate in building the same plan increases.

Chapter 7

Comparison with Routing Algorithms

In our domain implementation we refer to the function of planning new routes for disrupted circuits as Service Restoral. At first glance, it may appear that Service Restoral performs standard routing of disrupted circuits. The problem of routing circuits is well understood and indeed, many algorithms exist which route circuits in distributed networks. However, the assumptions concerning node connections as well as the overall objective of Service Restoral differs from those of the conventional algorithms. It is these differences which make existing algorithms inappropriate for Service Restoral. In the following paragraphs, several conventional algorithms are described briefly along with their assumptions and objectives. This description is then contrasted with the assumptions and purpose of Service Restoral.

Many distributed routing algorithms have been developed as a result of computer network construction. Most can be grouped into classes by their basic approach to the problem [11].

One class depends upon global knowledge residing at each processor node in the system. Algorithms in this category, such as that used in the ARPANET system

[20], require that each node have information about every trunk in the network along with an associated weight and time stamp. Whenever the weight of a trunk changes, flood messages are sent to maintain consistent information at each node. Using this trunk information and some graph algorithm such as Dijkstra's Shortest Path First algorithm [5], each node maintains routing tables for the shortest path between it and every other node in the system.

Another class of existing routing algorithms requires only condensed information at each node and uses "preferred next neighbor" tables to designate the next node in the shortest path to every possible destination in the network. Algorithms in this class [9, 19, 14, 25, 24] use update messages to maintain the "preferred next neighbor" tables. However, unlike the first class of algorithms described, a node sends update messages only to its neighbors.

This second class of algorithms was preferred over the first since less information about network topology was required at each node. Although the simplicity of these algorithms made them attractive, the updating procedure of these algorithms allowed temporary loops to occur in the distributed routing tables. As a result, another class of algorithms emerged. Algorithms in this class [10, 13, 21], also require only partial topology information and rely on "preferred next neighbor" tables¹. However, these algorithms establish and maintain the shortest path between two nodes through strict control of how the routing tables are updated. This strict control alleviates the problem of temporary loops occurring in the distributed routing tables.

Another algorithm which has gained recognition is one that uses a saturation technique [17]. Whenever a circuit needs to be routed, the source initializes a flood search of the network to find the destination. At the end of a predetermined time out, the destination selects the minimal cost route which it has received. Thus, each node only needs to know its nearest neighbors and the trunk groups associated with each search message.

¹The work by Gallager actually used a variation on these tables. Instead of sending all messages for a particular destination to a single preferred next neighbor, this message traffic was distributed to several preferred next neighbors based upon current network delays.

Each of these algorithms makes the same assumption about node connectivity, namely that every trunk into a node connects to the same main switching device. Given this assumption, it is senseless for a proposed route to pass through a node more than once. Each of these algorithms prevents (or attempts to prevent) the existence of such a route. It is also important to emphasize that each of the algorithms routes one circuit at a time with the goal of finding the route with minimal cost. The purpose of these algorithms is to dynamically route temporary circuits. Cost factors in these algorithms usually include at least the length of the route and sometimes the current demands upon the trunks traversed. This overall philosophy is applied to each circuit in isolation. That is, if more than one circuit needs to be routed, these circuits are routed without regard for their mutual existence.

In contrast, Service Restoral does not make the same assumption about the existence of a central switching device at each processor node. Service Restoral acts with a coarse grained level of processor distribution. Instead of a processor residing at each individual site, a processor is responsible for several sites, where each of these sites belongs to the same subregion. As a consequence, a processing node corresponds to a subregion and thus intrasubregion connectivity becomes an important issue. Service Restoral must work in an environment where multiple paths exist through the subregion which visit disjoint sets of sites. Thus it is possible that a plausible restoral route for a circuit may pass through a node more than once. In fact, a plausible restoral route may pass through multiple nodes more than once depending upon inter- and intranode (subregion) connectivity.

Another reason the conventional distributed routing algorithms are inappropriate for Service Restoral is that the overall philosophies differ. Whereas the existing algorithms are intended for temporary routing of previously nonexistent circuits, Service Restoral reroutes existing dedicated circuits which have been disrupted. Service Restoral attempts to make the most effective use of the network resources so as to restore as many circuits as possible. This is accomplished by collectively restoring circuits, making use of their previously reserved trunks as well as spare trunks and trunks that may be preempted. In order to determine the best utilization of the network resources, multiple alternatives for restoring each disrupted circuit must be

generated. From these alternatives, Service Restoral selects those plans which collectively restore the greatest number of circuits. Thus, merely determining the shortest or minimal cost path for a circuit is not the aim of Service Restoral. In fact, such a route may actually prevent the restoral of other circuits in the system. Instead, it is the intention of Service Restoral to move away from the dogmatic procedure of routing circuits in isolation to an approach which utilizes perceptions of what's happening in the system as a whole. By being aware of a group of circuits that have been disrupted, Service Restoral will be able to accurately reallocate network resources in the most effective manner.

Chapter 8

Future Directions

As a result of the preliminary experiments reported in this thesis, new directions for experimentation have become clear. Perhaps the most immediate is to design a network that models the scale of a real world communications network. It will be interesting to observe the effects upon the relative performance of the algorithms in a network which contains a greater volume of information.

Some modifications should be made to the plan generation phase to permit its use in a larger class of domains. One such alteration involves relaxing the definition of allocation in the model. Rather than requiring that resources be allocated for the duration of the satisfaction of a goal, the model should be modified to allow for the use of a resource for a period of time and then allow it to be relinquished for allocation for another purpose. Thus, the model will then be able to allow the dynamic scheduling of resources. In addition, the model as it exists makes an implicit assumption about the capabilities of the agents in the system. Namely, no two agents can bring a single plan to the same state. One solution to allow this situation would be to increase the information included in the support name. This might possibly be accomplished through a globally recognized encoding scheme for abstract state descriptions of plans.

Bibliography

- [1] S. Cammarata, D. McArthur, and R. Steeb, "Strategies of Cooperation in Distributed Problem Solving", *IJCAI-83*, pp. 767-770.
- [2] S. E. Conry, R. A. Meyer, and V. R. Lesser, "Multistage Negotiation in Distributed Planning", to appear in *Readings in Distributed Artificial Intelligence*, A. Bond and L. Gasser (eds.), Morgan Kaufman Publishers, California.
- [3] S. E. Conry, R. A. Meyer, J. E. Searleman, "A Shared Knowledge Base for Independent Problem Solving Agents", *IEEE Proceedings of the Expert Systems in Government Symposium*, October 1985.
- [4] D. D. Corkill, "Hierarchical Planning in a Distributed Environment", *IJCAI-79* pp. 168-175.
- [5] E. W. Dijkstra, "A Note on Two Problems in Connection with Graphs", *Numerical Mathematics*, vol. 1, pp. 269-271, 1959.
- [6] E. H. Durfee and V. R. Lesser, "Using Partial Global Plans to Coordinate Distributed Problem Solvers", *IJCAI-87* pp. 875-883.
- [7] G. W. Ernst and A. Newell, *GPS: A Case Study in Generality and Problem Solving* (Academic Press, New York, 1969).
- [8] R. E. Fikes and N. J. Nilsson, "STRIPS: A New Approach to the Application of Theorem Proving to Problem Solving", *Artificial Intelligence*, vol. 2, no. 3-4, pp. 189-208, Winter 1971.
- [9] L. R. Ford and D. R. Fulkerson, *Flows in Networks*, Princeton, NJ:Princeton University Press, 1962.

- [10] R. G. Gallager, "A Minimum Delay Routing Algorithm Using Distributed Computation", *IEEE Transactions on Communications*, vol. COM-25, no. 1, pp. 73-85, January 1977.
- [11] J. J. Garcia-Luna-Aceves, "A New Minimum-Hop Routing Algorithm", *IEEE INFOCOM '87 Proceedings*, San Francisco, CA, April 1987.
- [12] M. Georgeff, "A Theory of Action for Multiagent Planning", *IJCAI-84*, pp. 121-125.
- [13] J. M. Jaffe and F. M. Moss, "A Responsive Routing Algorithm for Computer Networks", *IEEE Transactions on Communications*, vol. COM-30, no. 7, pp. 1758-1762, July 1982.
- [14] J. Jubin, "Current Packet Radio Network Protocols", *IEEE INFOCOM '85 Proceedings*, Washington, DC, March 1985.
- [15] A. L. Lansky "Behavioral Specification and Planning for Multiagent Domains", Technical Note 360, Artificial Intelligence Center, SRI International, Menlo Park, California, November 1985.
- [16] A. L. Lansky "Localized Event-Based Reasoning For Multiagent Domains", Technical Note 423, Artificial Intelligence Center, SRI International, Menlo Park, California, January 1988.
- [17] G. Ludwig and R. Roy, "Saturation Routing Network Limits", *Proceedings of the IEEE*, vol. 65, no. 9, Sept. 1977.
- [18] D. MacIntosh and Susan Conry, "SIMULACT: A Generic Tool for Simulating Distributed Systems", NAIC Technical Report TR-8714, Rome, NY.
- [19] J. McQuillan, "Adaptive Routing Algorithms for Distributed Computer Networks", Bolt Beranek and Newman Inc., BBN Report 2831, May 1974.
- [20] J. M. McQuillan, I. Richer, E. C. Rosen, "The New Routing Algorithm for the ARPANET", *IEEE Transactions on Communications*, vol. COM-28, no. 5, pp. 711-719, May 1980.

- [21] P. Merlin and A. Segall. "A Failsafe Distributed Routing Protocol", IEEE Transactions on Communications, vol. COM-27, no. 9, Sep' 1979.
- [22] J. S. Rosenschein and M. R. Genesereth, "Deals Among Rational Agents", IJCAI-85, pp. 91-99.
- [23] Reid G. Smith "The Contract Net Protocol: High Level Communication and Control in a Distributed Problem Solver", IEEE Transactions on Systems, Man, and Cybernetics, vol. SMC-10, no. 12, December 1980.
- [24] W. D. Tajibnapis, "A Correctness Proof of a Topology Information Maintenance Protocol for a Distributed Computer Network", Communications of the ACM, vol. 20, pp. 477-485, 1977.
- [25] J. Westcott and J. Jubin, "A Distributed Routing Design for a Broadcast Environment", Conference Record of IEEE Military Communications Conference, Boston, MA, vol. 3, pp. 10.4.4-10.4.5, October 1982.
- [26] D. E. Wilkins, "Domain-Independent Planning: Representation and Plan Generation", Artificial Intelligence, vol 22, pp. 269-301.

CONCURRENCE FORM

The Rome Air Development Center requests the continuation of the AFOSR fellowship for Mr. Randall P. Pope, studying Distributed Processing at Clarkson University.

Give a brief statement of laboratory and/or Mr. Richard Metzger's (fellow's mentor) involvement with Mr. Randall P. Pope.

Mr. Metzger has received and reviewed Mr. Pope's thesis. He has had discussions with both Mr. Pope and his advisor Professor Meyer with regard to his progress. Mr. Pope is making excellent progress in his academic studies and will be invited to come to RADC during the summer break.

Richard Metzger 2-10-89

Chief Scientist

Date

Richard Metzger

Mentor

Date

08 FEB

S-789-000-020

FEB 16 1989

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Randall P. Pope

Semester: Fall 1988

University: Clarkson University

Subcontract: S-789-000-020

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Course	Grade	Credit Hours
Digital System Design	A	3
Introduction to Robotics	A	3
Seminar	Pass	1
Thesis Credit	Pass	5

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

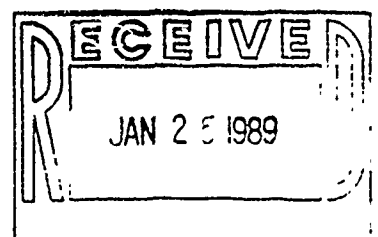
During the fall semester, I completed the requirements for my master's degree. I defended my thesis on September 8 and it was accepted by the thesis committee. A copy of my thesis is enclosed. In addition, I took the Ph.D. Induction exam at Clarkson and I have been notified that I passed.

"I certify that all information stated is correct and complete."


Signature/Fellowship Recipient

Randall P. Pope
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4963C



CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Randall P. Pope is making satisfactory academic progress toward a Ph.D. in the area of Distributed Processing in the discipline of Artificial Intelligence for the Fall 1988 semester."



Signature/Advising Professor

Robert A. Meyer

TYPED NAME/TITLE OF ADVISING
PROFESSOR

4963C

CONCURRENCE FORM

The Aero Propulsion Laboratory requests the continuation of the AFOSR fellowship for Mr. James Seaba, studying Combustion Systems/Mechanical Engineering at University of Iowa.

Give a brief statement of laboratory and/or Dr. M. Roquemore (fellow's mentor) involvement with Mr. James Seaba.

Mr Seaba worked for 8 weeks this summer at the Aero Propulsion and Power Laboratory as part of the Summer Graduate Research Program. He was studying the lifting process in jet diffusion flames. Mr Seaba used some of the unique optical equipment and combustion facilities at APPL in these experiments. Mr Seaba is currently analyzing the data that was collected this summer. This research is being performed under the direction of Prof. L. D. Chen of the University of Iowa and Dr W. M. Roquemore (APPL), who are Mr Seaba's thesis advisor and mentor, respectively. The results of this study will be included as part of his Ph D thesis. We are very pleased with the progress Mr Seaba is making on the AFOSR Fellowship program.

Edward J. Moran 10 Oct 89
Chief Scientist Date

W.M. Roquemore 11 Oct 89
Mentor Date

S-789-000-021

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. James P. Seaba

Semester: Spring 1989

University: The University of Iowa

Subcontract: S-789-000-021

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Statistical Thermodynamics Grade A-

Explained ensembles and related ensemble systems to thermodynamics. Developed models for mono, di, and poly atomic molecules and related these models to thermodynamic properties (averaged).

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Completed work on inverse diffusion flame burner. wrote and presented paper on this work at the Central States Combustion Institute meeting at Durham N. C. in Spring 1989.

Looked at diffusion flames in the lab relative to lift and blowout. Designed and built 3-D traversing motion optics to take data in the combustion chamber

"I certify that all information stated is correct and complete."

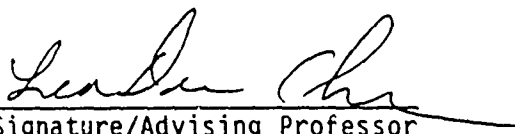
James P. Seaba
Signature/Fellowship Recipient

James P. Seaba
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4964C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. James P. Seaba is making satisfactory academic progress toward a Ph.D. in the area of Combustion Systems/Mechanical Engineering in the discipline of Mechanical Engineering for the Summer 1989 semester."


Signature/Advising Professor

Lea-Der Chen

TYPED NAME/TITLE OF ADVISING
PROFESSOR

4964C

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. James P. Seaba

Semester: Summer 1989

University: The University of Iowa

Subcontract: S-789-000-021

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

None

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

*Participated in LGFP, earned stipend for summer.
Ran experiments on the stability of diffusion flames.
Used a 2-D LDV system to characterize the annular
jet flow field. Also diluted the fuels with inert (N₂)
and recorded lift points at several mixture fractions.*

See USAF-UNIS Summer Research program for LGFP fellows. Reper
"I certify that all information stated is correct and complete."

James P. Seaba
Signature/Fellowship Recipient

James P. Seaba
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4964C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. James P. Seaba is making satisfactory academic progress toward a Ph.D. in the area of Combustion Systems/Mechanical Engineering in the discipline of Mechanical Engineering for the Spring 1989 semester."



Signature/Advising Professor

Lea-Der Chen

TYPED NAME/TITLE OF ADVISING
PROFESSOR

4964C

CONCURRENCE FORM

The Aero Propulsion Laboratory requests the continuation of the AFOSR fellowship for Mr. James P. Seaba, studying Combustion Systems/Mechanical Engineering at The University of Iowa.

Give a brief statement of laboratory and/or Dr. W. M. Roquemore's (fellow's mentor) involvement with Mr. James P. Seaba.

Mr Seaba has been a coauthor on a paper entitled "Buoyant Diffusion Flames." This paper was presented at the 22nd Symposium (International) on Combustion/The Combustion Institute, 1988. He is currently working on lifted jet flames and is planning to work at APPL this summer using some of our unique diagnostic capabilities. Based on Mr Seaba's performance, I recommend his application for the Student Fellows Program be renewed.

Edward J Curran 11 Apr 89

Chief Scientist Date

W. M. Roquemore

Mentor Date

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. James P. Seaba

Semester: Fall 1988

University: The University of Iowa

Subcontract: S-789-000-021

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

58:245 - Diffusion Transport : Grade A⁺ : Covered heat conduction and diffusive transport of heat, mass, and momentum. Analytical and numerical solution techniques to diffusion equation were discussed.

58:299 - Research : Grade Satisfactory . See below

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

- 1) Completed experiment of an inverse diffusion flame.
- 2) Reduced data and compared to the conventional diffusion flame data. This required an extensive ~~current~~ literature search with respect to diffusion flames, lift-off, stability heights, and blow-out. The literature search is the main information regarding my Ph.D. thesis work. The inverse diffusion flame experiment will be presented at the Combustion Institutes

"I certify that all information stated is correct and complete." Spring Conference
in May 1989.

James P. Seaba
Signature/Fellowship Recipient

James P. Seaba
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4964C